

Fundamental Aeronautics

Hypersonics Project

Reference Document

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This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Fundamental Aeronautics Hypersonics research project. It contains reference to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a completed research plan.

1. Technical Plan

Relevance

The need for the National Aeronautics and Space Administration (NASA) Aeronautics Research Mission Directorate (ARMD) Hypersonic Project is based on the fact that all access to earth or planetary orbit, and all entry into earth's atmosphere or any heavenly body with an atmosphere from orbit (or super orbital velocities) require flight through the hypersonic regime. The hypersonic flight regime often proves to be the design driver for most of the vehicle's systems, subsystems, and components. If the United States wishes to continue to advance its capabilities for space access, entry, and high-speed flight within any atmosphere, improved understanding of the hypersonic flight regime and development of improved technologies to withstand and/or take advantage of this environment are required.

Today, rocket-powered expendable launch vehicles reach hypersonic speeds in the upper atmosphere while transporting payloads to orbit; low L/D, unpowered hypersonic entry vehicles return to earth from orbit and other heavenly bodies, and transit the atmospheres of other planets to land robotic exploration systems; and the Space Shuttle, a semi-reusable system, is used to transport humans to orbit and back. While these are extraordinary accomplishments, hypersonic flight is far from routine, and its potential is not fully exploited. Since the early 1950s, hypersonics research has experienced numerous boom and bust cycles. The successful systems developed over this time period (X-15, Apollo, Space Shuttle, etc) are products of the boom cycles, but once these systems were developed, most hypersonics foundational research was terminated, requiring regeneration of capabilities when the next vehicle development cycle started. There is a unique opportunity at this point in time to capitalize on a core of hypersonics researchers within NASA, Department of Defense (DoD), and industry that was trained in hypersonics during the boom associated with the NASP, X-33, and X-34 reusable launch vehicle programs, and recent planetary and earth entry programs such as Pathfinder, Stardust, and Mars Exploration Rover. While the reusable launch vehicle programs mentioned above never resulted in an operational system, many advancements in design and analysis tools, test techniques, and understanding of the basic physics of hypersonic flow, materials and structures were made. Some of these advancements have been applied to the design of other systems (planetary probes for example) and flight experiments (X-43 and X-51), but much is still left to be learned. While there clearly exists the ability to design certain hypersonic systems, designers often resort to large margins to mitigate uncertainties, which reduce system capabilities and increase costs. Large uncertainties in aerodynamics, aerothermodynamics, material properties, structural response, durability, and integrated system performance often kill or significantly alter mission plans or result in poor input to risk assessment. A good example of this uncertainty occurred on the last shuttle flight (STS-114) when an extra space walk was required to remove gap filler protruding from between tiles. The spacewalk was considered lower risk than leaving the gap filler protruding because no prediction of the enhanced re-entry heating due to the protrusion (shock heating, premature turbulent boundary layer transition) could be made with a sufficient confidence level. In addition to deficiencies in the understanding of some basic physical phenomena and the resulting predictive uncertainties, substantial deficiency also exists in the ability to predict operational cost, safety and reliability of these systems, much less optimize a system on such metrics. Developing methods and tools that adequately model fundamental physics, and allow credible optimization for operational factors, will allow highly beneficial hypersonic systems to emerge. Today, hypersonics is at the same crossroads that supersonics was fifty years ago. A stable, long term commitment to investment in foundational hypersonics research will allow sufficient understanding of the underlying physics to improve design methods to the level of certainty required to fully utilize the possibilities of hypersonic flight and allow it to become routine.

A primary goal of the Hypersonics Project is to develop predictive capabilities enabling both the civilian and military communities to build hypersonic systems that meet their specific needs. Figure 1 presents a portfolio of “vision” entry, ascent, and cruise systems. The major system characteristics are briefly described for selected entry missions such as crew exploration vehicle (CEV) and planetary entry vehicles for Mars, giant planets, and large satellites; for advanced reusable space access missions such as airbreathing two-stage-to-orbit (TSTO) vehicles and single-stage-to-orbit (SSTO) vehicles; and for cruise systems such as strike and global reach vehicles. The space access SSTO vehicles and TSTO vehicles not only have ascent systems but also entry, descent, and landing (EDL) systems. In addition these airbreathing vision systems are further categorized in Figure 1 by scramjet operational Mach number, or maximum airbreathing engine Mach number ($M_{a/b}$); whereas the pure entry systems are categorized by entry velocity in km/s. These speed regimes along with the mission class of the vision system tend to define the technologies and design methods required, but there are also significant overlaps in technologies and methods between mission classes and/or speed regimes. The NASA Hypersonics Project plans to take advantage of these overlaps to address as many critical technologies and design methods as possible by focusing on two high pay-off NASA unique missions which cover much of the required ground, one mission focused on entry and the other on space access.

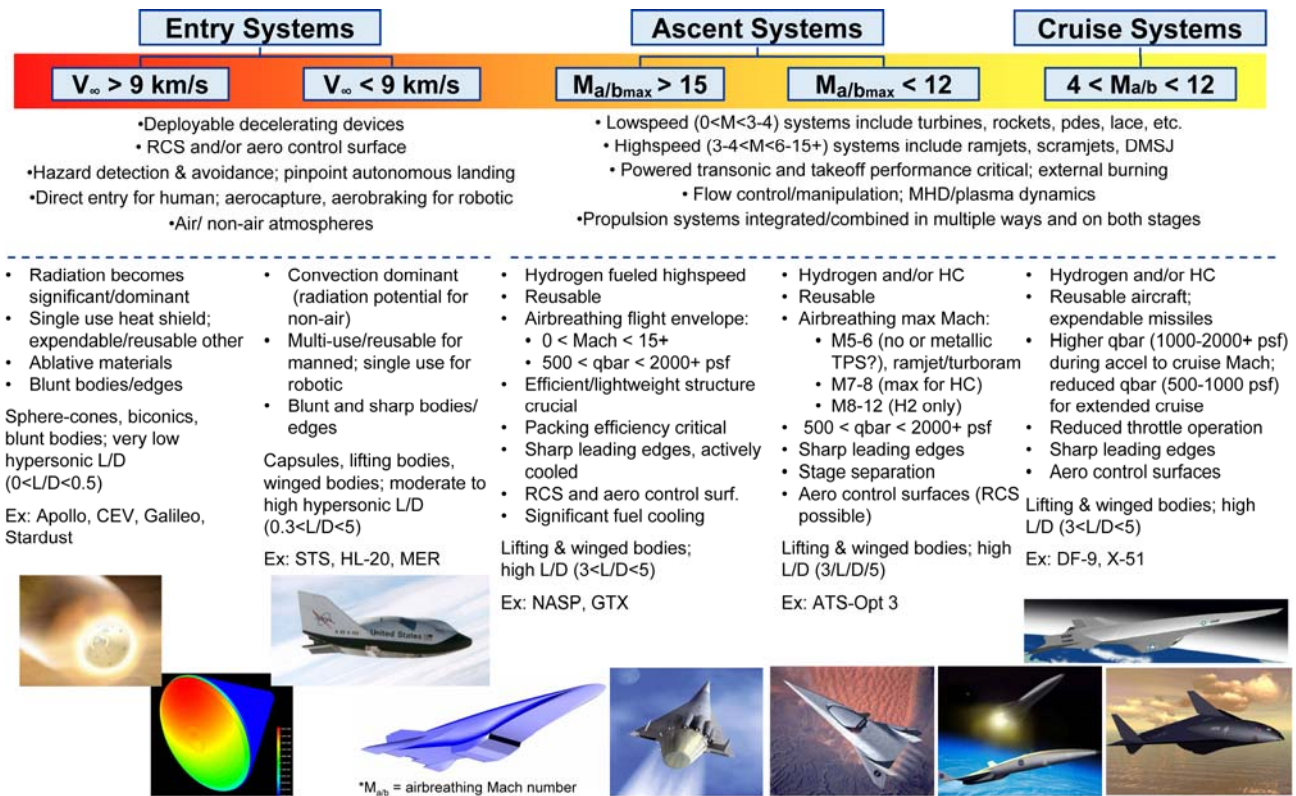


Figure 1. Characteristics of Entry, Ascent, and Cruise Systems.

Two mission classes have been chosen by the Hypersonics Project to focus technology and methods development efforts. These are Highly Reliable Reusable Launch Systems (HRRLS) and High Mass Mars Entry Systems (HMMES). These two mission classes address the technology and methods needs shown on the second and fourth columns in Figure 1; each addresses an area critical to future NASA needs while providing a basis for the more challenging technology and methods development work represented in columns one, three, and five of Figure 1. Specific high pay-off challenges from these more challenging mission classes will also be pursued such as shock layer radiation modeling from

column 1 and hypervelocity combustion physics from column three. In addition many of the technologies and methods developed for use on column two and four missions are also applicable to missions in other columns, therefore close collaboration is planned with other NASA mission directorates (ESMD and SMD), the DoD, and industry to extend the Nation's hypersonics capabilities as far as possible.

The HRRLS mission class was chosen to build on work started in the Next Generation Launch Technology Program (NGLT) to provide new vehicle architectures to increase the reliability of launch vehicles dramatically. The current state-of-the-art (SOA) for reliability of launch vehicles is approximately 1 loss in 50 missions for expendables and less than 1 in 100 for manned systems such as the Space Shuttle. These low reliability numbers reduce the market for launches and thus increase the cost of launching cargo and people to orbit. The NGLT Program spent considerable resources over several years studying a wide variety of future launch vehicle concepts including vertical take-off horizontal landing (VTHL) all rocket systems, horizontal take-off horizontal landing (HTHL) and VTHL Rocket Based Combined Cycle (RBCC) systems, and HTHL Turbine Based Combined Cycle (TBCC) systems. When reliability was used as the figure of merit (FOM) to compare these vehicle types, airbreathing systems out performed all rocket systems by orders of magnitude, see Figure 2. These reliability improvements were a result of higher efficiencies of the airbreathing systems allowing higher inert mass fraction to increase structural and systems margins so safety could be designed in. The HTHL systems also had more abort options available due to their high L/D. Airbreathing systems also performed very well vs. all rocket launch vehicles when compared on other FOMs such as mission flexibility and cost per pound of payload to orbit. While the exact magnitude of the improvements indicated in these study results can be questioned, the trends and the obvious potential for large reliability improvements due to airbreathing propulsion systems are clear.

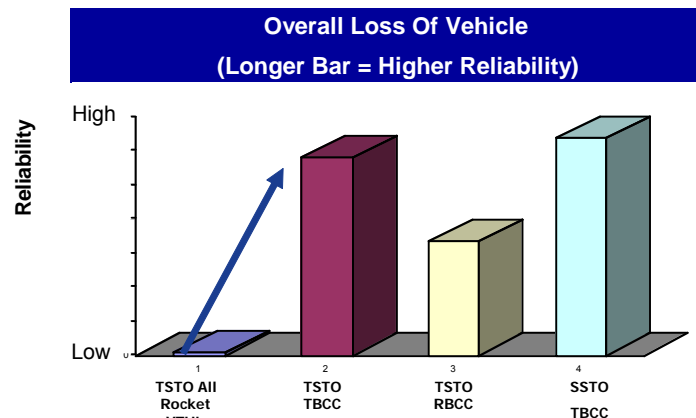


Figure 2. Increase in reliability of launch vehicles with different airbreathing propulsion options. See Bilardo, et al. AIAA-2003-5265.

These NGLT studies serve as a departure point to focus the HRRLS technology and methods work proposed by the current Hypersonics Project. The current project will primarily focus, at least initially, on TSTO TBCC systems which were identified as the highest pay-off systems by the end of NGLT. For these vehicles, the milestones and metrics, and the technical approaches proposed by the current Hypersonics Project are consistent with technology development priorities, roadmaps, and metrics developed with great effort and expense by NASA (with participation by industry and academia) under the NGLT Program, and jointly by DoD and NASA under the High-Speed/Hypersonics Pillar of the National Aerospace Initiative. The details of these technology development plans are restricted, but they are summarized in several unrestricted conference papers such as McClinton et al, IAC-04-V.8.08. Figure 3 lists the major technology areas required for a TSTO TBCC HRRLS type vehicle. The figure

depicts areas that require significant work in terms of both technology development and physics-based modeling. The Hypersonics Project is proposing work in many of these areas. Priority was given to those tasks that cross-cut many of the mission areas in Figure 1, were important to securing collaboration with partners, and lined up with available NASA expertise and capabilities.

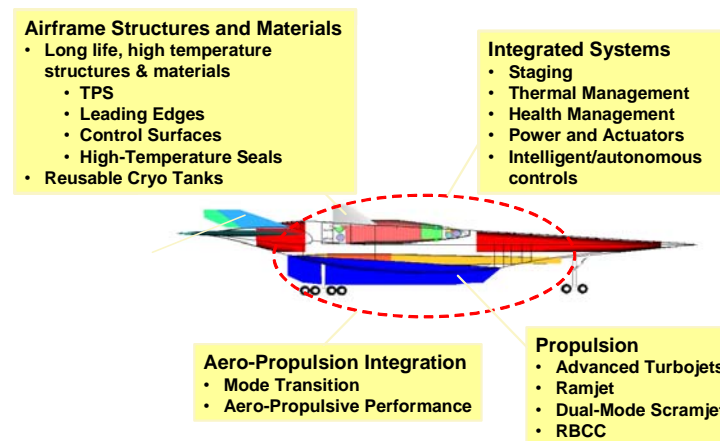


Figure 3. Key technology requirements for TSTO TBCC systems with a staging Mach number of Mach 12 or less.

The HMMES mission was chosen as a focus of the project because dramatic improvements in our capability to safely land large payloads on Mars are required to enable large science and human exploration missions. The SOA for successfully landing payloads on Mars is less than 1 metric ton with an accuracy of approximately a 100 km footprint around the target. Recent studies (“Mars Exploration Entry, Descent and Landing Challenges” Braun and Manning IEEE Paper 06ID0076 available at <http://hdl.handle.net/1853/8390> and “The Mars EDL Problem” Powell, et al, presentation to the NASA EMB April 4, 2006) have shown that the current technology, which was developed for the Viking Landers in the 1970s, cannot be extended to payload masses much beyond 1 metric ton. Plans for human and large science missions to Mars require nearly two orders of magnitude increase in mass landed safely, and targeting improvements of 3 to 4 orders of magnitude. The crux of the problem is that the Mars atmosphere is thick enough to cause significant thermal heating, but so thin that terminal velocities are very high. These factors combined with the need for precise targeting requirements to enable landing at points of scientific interest and/or rendezvous with prepositioned assets cause daunting challenges for the system designer.

Solving the problem of safely landing large payloads on the surface of Mars requires analysis of a number of technology options over the entire EDL speed range from high hypersonic speeds to subsonic speeds as shown in Figure 4. The Hypersonics Project proposes to collaborate with technologists supported by Exploration Systems Mission Directorate (ESMD) and Science Mission Directorate (SMD) to undertake a systems analysis trade study based on the taxonomy in Figure 4 aimed at identifying the decelerator approaches with highest likelihood of success, and identifying key hypersonic technologies and modeling challenges that require further work. This study along with a number of well known technology and modeling needs for entry vehicles (illustrated in Figure 5) form the basis of the proposed work supporting entry vehicle technology.

Human Mars EDL Decelerator Taxonomy

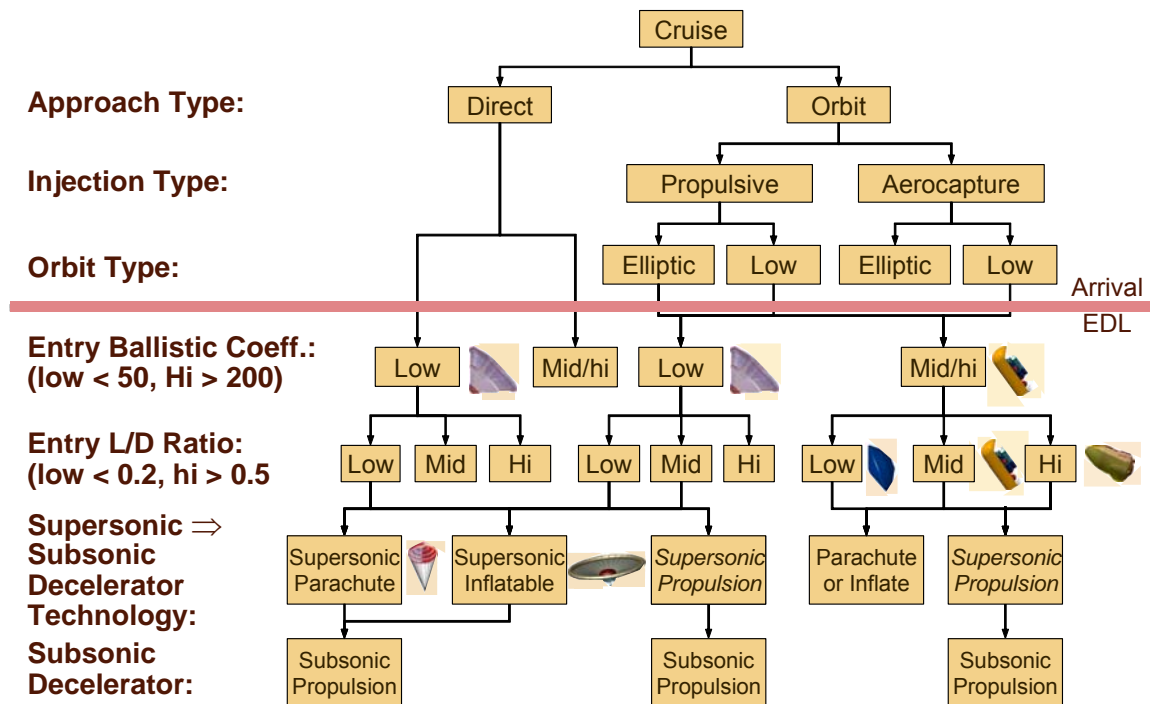


Figure 4. Mars EDL Decelerator Taxonomy. Extracted from “The Mars EDL Problem”
Powell, et al., presentation to the NASA EMB April 4, 2006

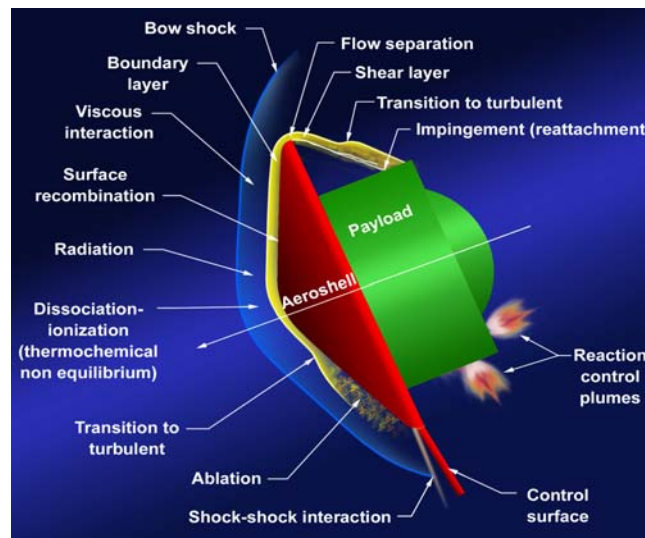


Figure 5. Entry vehicle technology
and modeling improvement needs.

The work focused around the HRRLS and HMMES missions will be organized at multiple levels, where the highest level objective is to develop system-level, physics-based multi-disciplinary analysis and design optimization predictive capabilities, incorporating uncertainties. To achieve this goal at the system level requires investment in a comprehensive portfolio of research and technology development (R&D) activities.

The R&D portfolio is guided by the “pull-push” philosophy where technologies and capabilities flow up to the system level from all the lower levels (Foundational Physics and Modeling, Discipline, and Multi-Disciplinary), and requirements and needs flow down from the system level to the lower levels. This portfolio is traceable to the potential operational vision systems illustrated in Figure 1. The capability levels are presented in two equivalent forms in Figure 6. The first version illustrates the “pull-push” philosophy and the milestone numbering scheme, and the second shows more detail of the discipline research areas at each level and some of the information flow between disciplines.

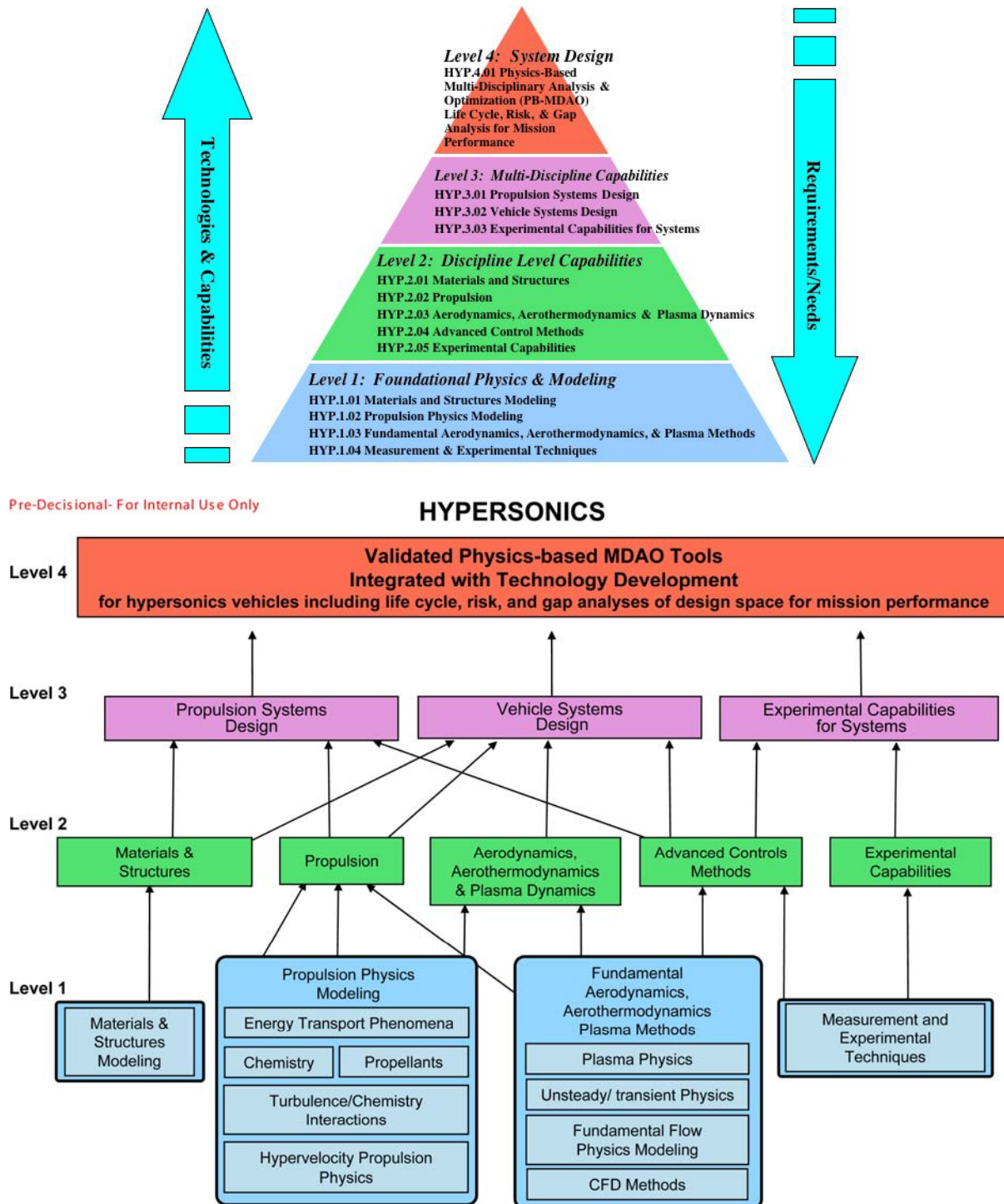
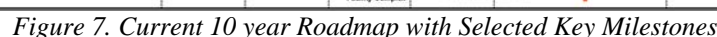


Figure 6. Research and Technology Development Philosophy and Capability Levels

In order to meet the required modeling and technological challenges, the Hypersonics Project has developed a set of milestones with associated metrics and way points. The milestones have quantifiable metrics that can be used to validate and measure progress toward or completion of technical goals, while the way points are important baselining activities such as SOA assessments or demonstration of new capabilities that in and of themselves have no measurable milestone, but lead to measurable improvements. If these efforts are successful, not only will considerable advancements in the understanding of the hypersonic environment be attained, but significant advancements in the technologies and design methods that are required for new or improved hypersonic vehicle capabilities will result. The milestones, metrics, way points and associated tools, methods, and technologies will be reviewed and adjusted on an annual cycle depending on progress in the research area and updated Project resources and priorities.

Key milestones and way points shown in the Milestone roadmap below are a subset of the total milestone list, which is not included in this document for brevity and will be maintained under configuration control by the Project Manager. Milestones and way points not shown contribute to the success of these key milestones and way points or contribute to alternative methods of reaching project goals. All milestones and way points shown in the roadmap are listed in tables in the appropriate Technical Approach section along with other pertinent information such as a description of the activity, expected date of completions, metric, and deliverable. Many milestones presently require partnerships with DoD or Industry to be fully successful. Not all of these partnerships have been finalized.



Technical Approach

The following sections describe the Technical Approach to be used at each level to meet the project milestones described in the previous section. The section numbering scheme follows that used for the milestones starting with level 1 Foundational Physics and Modeling, and ending with level 4 physics-based multi-disciplinary analysis and optimization (PB-MDAO).

HYP.1.01—Materials and Structures Modeling

The objective of the Materials and Structures (M&S) Discipline Team is to develop material technology, structural concepts, and computational tools that will provide the means for long-term advancement of structural capabilities for hypersonic airframe, propulsion, and lightweight tank applications. These M&S advancements will feed evolving structural design and analysis tools (Figure 8), and eventually enhance level 4 PB-MDAO capabilities.

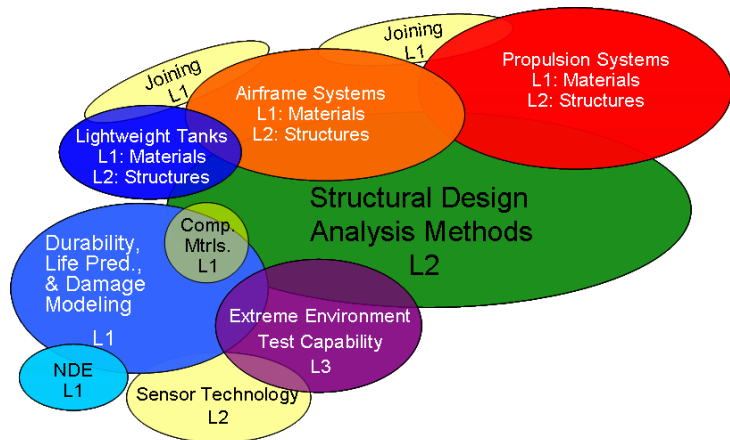


Figure 8. Hypersonic M&S components showing Level 1 (L1) and Level 2 (L2) research and integration.

The M&S Team refined the technology roadmap developed by the ARMD workshops to selectively mature critical structure technologies applicable to the TSTO HRRLS and HMMES missions. In addition to technology advancements, the M&S Team will improve system-level capabilities in the areas of (1) structural design and analysis and (2) material durability, life prediction, and damage modeling. Efforts at level 1 center on developing fundamental understanding and physics-based modeling and link these developments to the validation of advanced structural concepts and analysis tools at level 2. The primary focus will be on high pay-off hypersonic materials having cross-cutting applications to the TSTO HRRLS and HMMES hypersonic vision vehicles. The level 1 M&S efforts will focus primarily on structural systems that can reliably and safely operate in the extreme environments of hypersonic flight. The M&S level 1 roadmap (Figure 9) is focused on four technology “themes” detailed below.

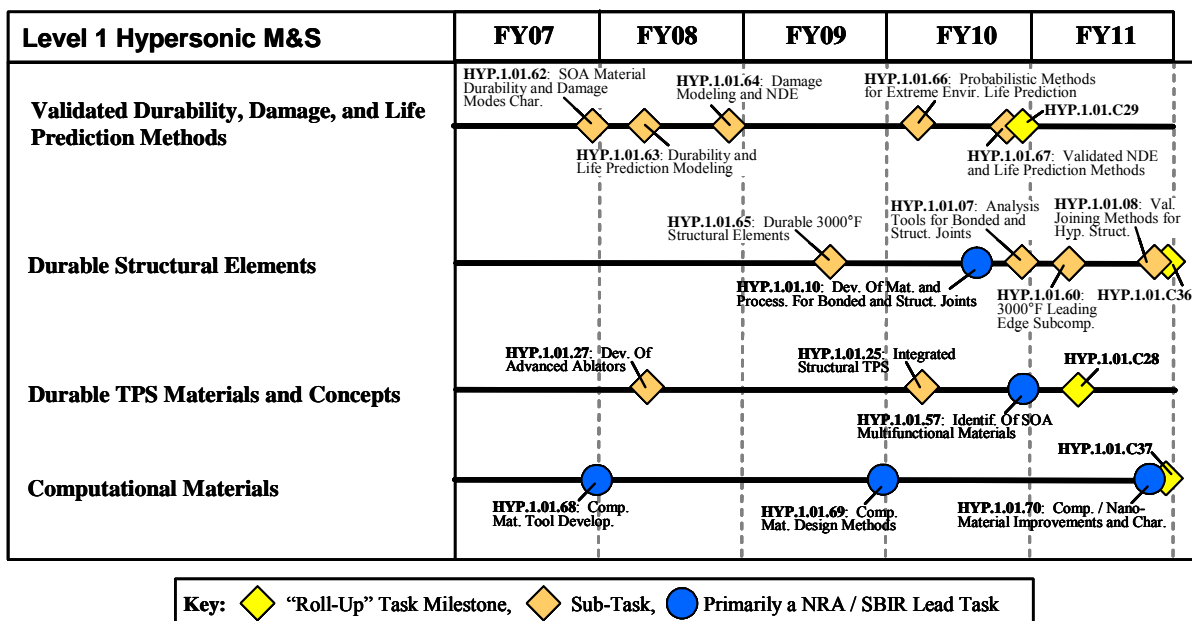


Figure 9. M&S Level 1 Milestone Roadmap.

Validated Durability, Damage, and Life Prediction Methods.—The primary technical challenge to materials used in either single- or multi-mission hypersonic vehicles operating at extreme conditions is the development of design tools and fabrication processes for durable, damage tolerant, lightweight structural systems. For this effort, several high pay-off material systems requiring focused research have been identified: carbon fiber reinforced silicon carbide composites (C/SiC) for airframe, leading edge, and control surface applications at temperatures between 2400 to 3000 °F; silicon carbide fiber reinforced silicon carbide composites (SiC/SiC) for leading edges and scramjet applications at temperatures between 2000 and 2800 °F; ultra-high temperature ceramics (UHTC) for coatings and leading edge applications at temperatures in excess of 3000 °F; titanium and gamma titanium-aluminide (γ -TiAl) for turbine compressor applications at 1200 to 1500 °F; and ablators for planetary entry at temperatures in excess of 3000 °F.

A first-year effort at level 1 will focus on establishing baselines for known material performance (HYP.1.01.62) that can be used to identify technology gaps and limitations that need to be addressed with additional testing characterization and material process improvements throughout the program. Established baselines and evolving test characterizations will also be used to develop design databases that support prediction models for material durability and remaining life, damage models that quantitatively couple non-destructive evaluation (NDE) techniques with material performance, and methods to incorporate material uncertainties in structural design, and validate durability and life models (HYP.1.01.63). Integrated durability and life models will incorporate the required material constitutive dependencies on exposure time, temperature, load, and environment. These models will feed the development of integrated structural design and analysis tools at level 2 (HYP.02.01.C04) to provide reduced design cycle time and improved assessment of structural performance, life, and operational reliability over single- and multi-mission vehicle requirements.

Durable Structural Elements.—A key technical issue for candidate hot-structure materials is environmental durability and robust structural joining and fabrication technologies. This effort will focus on the following two areas:

- (1) Material improvements to enhance temperature capabilities and oxidation resistance of candidate hypersonic materials through material processing improvements. Specific material improvements for the high pay-off systems identified include enhanced oxidation resistance for the C/SiC composite to extend service life and design stress (HYP.1.01.65), improved creep resistance of the SiC/SiC composite to extend service temperature to 3000 °F (HYP.1.01.65), improved durability of the UHTC materials, and improved impact damage tolerance of γ -TiAl. If successful, material improvements will be used to develop a 3000 °F leading-edge subcomponent (HYP.1.01.60) for potential level 2 validation tests (HYP.2.01.C03).
- (2) Robust joining and integration technologies are required to provide an affordable route to processing, manufacturing and assembly of realistic vehicle airframe and propulsion components. This level 1 activity will focus on developing technologies that enable fabrication and/or assembly of complex components possessing reproducible and predictable design properties (HYP.1.01.07, 08, and 10). Since this technology area strongly cross-cuts the interests of other FA projects, Hypersonics will leverage its resources by participating in Inter-Disciplinary Groups (IDG) to develop promising technologies and, when needed, extend use to hypersonic specific applications. Additional support will be sought through Small Business Innovative Research (SBIR) resources. NASA will guide technology developments and provide the fundamental understanding required to characterize design metrics. The goal is to develop and demonstrate a viable

suite of joining and repair technologies that will enhance robust design tools for complex structural components.

Durable TPS Materials and Concepts.—Both the HMMES and HRRLS missions require unique TPS developments to make these missions operationally feasible. For the HMMES mission, some entry profiles of interest into Mars yield coupled radiation and convective heating that can not be mitigated using current ablator technology. As a result, the M&S Discipline Team is focused on the development of mid-density ablators for Mars missions and advanced ablators (multifunctional ablators with radiation heating inhibitors) for the even more severe entry environments for larger Gas Giants (HYP.1.01.27 and HYP.1.01.57). Reducing structural component unit weight, while increasing life and damage tolerance, will be a goal for any HRRLS vehicle. One developmental area will be structurally integrated acreage TPS concepts where lighter and more resilient structures resist both the aerodynamic loading and thermal heating associated with hypersonic flight (HYP.1.01.25).

Computational Materials.—Computational materials development (CMD) methods from quantum to continuum levels will be used to guide and optimize material development efforts (HYP.1.01.C37). The work proposed herein is to adapt, modify, and further develop existing multi-scale and multi-physics based materials design and simulation capabilities to TPS materials design problems relevant to hypersonics, and create an integrated tool that augments CMD efforts proposed under other ARMD FA efforts. The proposed CMD tools development and simulation effort will focus on improving the environmental resistance of coatings and substrates for C/SiC, SiC/SiC, UHTC, and ablator materials then progress to nano-structured materials to enhance emissivity and thermal management. Selected TPS materials will be fabricated and characterized to validate the CMD platform.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.01.C29 2010 Q4	Validated Durability, Damage, and Life Prediction Methods	HYP.1.01.62 HYP.1.01.63 HYP.1.01.64 HYP.1.01.66 HYP.1.01.67	Develop physics based durability, damage, and life prediction models for multi-mission structural analysis and design of hypersonic components.	Predictions within 10% of a B-basis design allowables for arbitrary multi-mission loads.	Models and documentations.
HYP.1.01.62 2007 Q4	SOA Material Durability and Damage Modes Characterization		Assemble baseline design database and identify gaps relating to SOA hypersonic materials for multi-use applications (i.e., CMC's, UHTC's, high-temperature metallics, ablators, tank materials (Al-Li & PMC)). Identify gaps and conduct material tests with available test articles.	Way point--no metric	Documented baseline design database for the SOA hypersonic materials which emphasizes multi-cycle material characteristics
HYP.1.01.63 2008 Q2	Durability and Life Prediction Modeling	HYP.1.01.62	Develop durability models for combined damage interaction effects due to environmental and mechanical loading. Establish physics based analytical models to assess the impact of environmental and mechanical loading on remaining material life (Collaborative work with SFW and Aging Aircraft and Durability for metallics).	Predictions of material residual strength are within 10% of experimentally determined mean-value response.	Validated material durability and life prediction models for C/SiC and CVI SiC/SiC material systems. Documentation of models and any correlating test results.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.01.67 2010 Q4	Validated NDE and Life Prediction Methods	HYP.1.01.64	Validation of NDE techniques to distinguish and quantify extent of material damage and the relationship between damage to reduction in material properties such as stiffness and strength. Validation of methodologies for physical modeling of NDE techniques.	Predict life based on NDE detected material defects and compare to within 10% of experimentally determined values.	Models, NDE procedures and documentation of material life prediction methods for hypersonic environments.
HYP.1.01.C36 2011 Q4	Durable Structural Elements	HYP.1.01.07 HYP.1.01.08 HYP.1.01.10 HYP.1.01.60 HYP.1.01.65	Development of advanced structural concepts and components for extreme environments.	Refer to sub-milestones HYP.1.01.65 HYP.1.01.08	3000 °F materials and fabrication techniques
HYP.1.01.65 2009 Q3	Durable 3000 °F Structural Elements	HYP.1.01.62 HYP.1.01.63	The key technical issue for hot structure materials is environmental durability (oxidation resistance). Material improvements for enhanced temperature applications of C/SiC, SiC/SiC, and UHTC's will be established by developing coatings and material process improvements.	Extend service temperature envelope of CVI SiC/SiC from 2400 to 3000 °F and 5 mission cycles; 3000 °F oxidation resistant coating for C/SiC; increase UHTC fracture toughness by 20+13%.	3000 °F composite system for airframe or combustor panel component and durable UHTC. Documentation of material processes and test results.
HYP.1.01.08 2011 Q4	Validated Joining Methods for Hypersonic Structures.	HYP.1.01.10	Validation of analysis and design tools for joining concepts. Evaluate joint performance through coupon, element, and subcomponent testing under combined loads.	Demonstrate analysis predictions to within 15% of experiment.	Design handbook for bonding and joining technology.
HYP.1.01.C28 2011 Q2	Durable TPS Materials and Concepts	HYP.1.01.25 HYP.1.01.27 HYP.1.01.57	Integrated structural TPS, advanced ablators, and multi-functional materials	Refer to sub-milestones HYP.1.01.25 HYP.1.01.27	Design rules and tools for lightweight, multi-functional TPS.
HYP.1.01.25 2010 Q2	Integrated Structural TPS	HYP.2.01.50 HYP.1.01.62	Using improved materials and concept, design and develop an integrated TPS (an airframe acreage hot structure integrated with TPS). <i>Anticipate Government or Industry partnership to fabricate test article.</i>	Demonstrate 10% reduction over System level 4 design goal for HRRLS airframe acreage weight allocation.	Multi-use subcomponent concept for a structurally integrated TPS system.
HYP.1.01.27 2008 Q2	Development of Advanced Ablators	HYP.1.01.62	Develop optimized mid-density ablators for Mars missions and advanced ablators for more severe entry environments, e.g., Gas Giants. Identify and segregate ablative materials into thermal performance regimes and identify regions of performance overlap.	Demonstrate tailorable multi-functional advanced ablator systems with densities from 0.25 to 1.0 g/cc.	Engineered ablator concepts with density ranging from 0.25 to 1.0g/cc and documentation of performance.
HYP.1.01.C37 2011 Q4	Computational Materials	HYP.1.01.68 HYP.1.01.69 HYP.1.01.70	Computational tools will be integrated into a computational materials design (CMD) platform capable of simulating materials properties across the nano-micro-mesoscopic scales and carefully validated against experiment.	Predict material properties to within 10% of measured values.	Computational materials design (CMD) system

HYP.1.02—Propulsion and Physics Modeling

The primary technical challenge of the Propulsion Discipline is to enhance the capability to predict flow path physics, fluid dynamic mechanisms (and interactions), and to define the propulsive environment. This will enable the development of efficient design tools applicable to the HRRLS mission and a variety of other hypersonic systems. To this end, the Propulsion Discipline research effort focuses on both the generation of databases derived from benchmark/component experiments and integrated

component experiments, and analysis of existing ground and flight databases coupled with analytic and modeling efforts to produce consistent physics-based models and tools. These activities leverage Fundamental Aeronautics Program (FAP) Hypersonic Discipline tasks (i.e., Aerodynamics/Aerothermodynamics and Plasmadynamics, Experimental Capabilities, Materials and Structures), industrial, academic, and government expertise; as well as, on-going hypersonic propulsion programs including but not limited to, FRESH-Fx, Office of the Secretary of Defense (OSD), RATTLRS, HiSTED, X51A, and Falcon. Hypersonic propulsion and physics modeling efforts will be subsequently discussed within two main areas: 1) Combustion Physics including chemistry, propellants, turbulence/chemistry interactions, and hypervelocity propulsion, and 2) Flow Physics including turbulence, mixing, boundary-layers, shock structures, stability modeling and non-equilibrium fluid-dynamic processes.

Combustion Physics (HYP.1.02.18/22/38/41/48/52/C02/C03).—Combustion physics and mechanisms modeling efforts focus on: 1) ignition and flame-holding, 2) turbulent flame propagation, inclusive of jet penetration, fuel/air mixing and combustion mechanisms (across the speed regime), 3) vitiated test media and facility contamination effects, 4) hydrogen-air /hydrocarbon-air kinetic mechanisms, and 5) multi-phase combustion processes. A series of “unit” experiments will be conducted using SOA diagnostic tools to quantify the operability (stability limits) of a generic hydrocarbon-fueled combustor. Physics-based ignition and flame-holding models will be developed utilizing existing data (NASA and OSD databases), and level 2 experimental data. Studies will be conducted to understand the effects of vitiation and scale on combustion. Opposed-Jet-Burner experiments will be conducted to quantify kinetic mechanisms and develop reduced hydrocarbon mechanisms, including the effects of endothermic additives. Level-2 hypervelocity (Mach >10) test data obtained at Hypersonic Pulse Facility (HyPULSE) will be used to develop high-speed combustion physics models. Operability and performance data from level-2 experiments will be used to validate reacting flow models and cycle-performance models relevant to RBCC and TBCC propulsion cycles.

Turbulent, chemically-reacting flow models will be developed and incorporated into computational algorithms. Existing and new experimental databases assembled under the current effort will be used to improve phenomenological turbulence and subgrid scale models for use in: 1) Reynolds-averaged Navier-Stokes (RANS) codes, 2) hybrid RANS/Large-Eddy Simulation (LES), 3) LES/PDF, and 4) PDF codes to simulate turbulent high-speed reacting flows. The current SOA for modeling scramjet engine flowpaths involves the use of RANS codes and engineering tools. Improved phenomenological models of turbulence, turbulent mixing and turbulent-chemistry interaction will be developed using data collected under the present program. Hybrid RANS/LES code capability will be extended by developing means of extracting synthetic turbulent structures from RANS regions to supply LES regions with resolved turbulent content. Development of LES methods that utilize subgrid PDFs to describe mixing and combustion at small scales will be further developed and refined. Lagrangian PDF methods for compressible reacting flow will be developed, and a PDF code will be written to model high-speed compressible flows typical of scramjet environments. Finally, development of high-order spatially and temporally accurate methods, and upwind biased flux schemes, will be undertaken, and the resulting algorithms will be incorporated into the RANS, RANS/LES and LES/PDF codes being improved or developed in this effort. Additionally, this effort also addresses unsteady combustion physics mechanisms related to detonative processes. These models will be used in level-2, -3 and -4 performance assessments.

Flow Physics (HYP.1.02.01/49/50/C09).—Advanced models are required to understand relevant flow physics and predict net-propulsive performance and operability limits unique to hypersonic air-breathing propulsion systems. Numerous fluid-dynamic issues, such as shock/boundary-layer interactions, shock-

shock enhanced heating mechanisms, transition processes (both natural and forced), primary- and secondary-flow mixing dynamics, and separated-flow fluid dynamics are important in the integrated design of hypersonic propulsion systems. For example, the flow physics associated with the interactions between the inlet shock structure and the inherently unsteady fan/compressor rotating shock structure must be understood to develop fan and compressor stability models, as well as to predict inlet operability margins. Also, advanced flow-control analysis, with aspiration and bleed models to assess performance and stability, must be incorporated within 3-D steady/unsteady computational tools. Improvements in scramjet isolator modeling are also required, in order to quantify the relevant shock-boundary interaction mechanisms associated with varying Reynolds number effects and inflow-distortion values dictated by realistic trajectory constraints. Isolator testing will be conducted to obtain 3-D velocity measurements to improve modeling capabilities, with emphasis on shock-boundary-layer interaction mechanisms. Furthermore, methods to interface different computational fluid dynamics (CFD) algorithms and turbulence models (with and without combustion) must be developed to couple stationary-frame inlet and nozzle-duct codes to rotating multi-passages turbo-machinery codes. Ultimately, these elements will be incorporated into multi-disciplinary tools and utilized in level-2, -3, and -4 studies. In summary, emphasis is placed on tasks that enhance the capability to quantify the mechanisms associated with the physics of hypersonic propulsion.

To augment these activities, NASA Research Announcement (NRA) efforts will be solicited in the generation of experimental datasets useful for the development of analytic models and analysis methodologies; as well as, associated novel experimental techniques that will enhance the SOA capabilities to acquire new datasets for analysis and modeling improvements. Additionally, both the NRA and SBIR process will solicit innovative concepts, in novel propulsion fluid dynamics such as magneto-hydrodynamics, advanced fluidic-thermal management, and analysis methods applicable to the high-heat flux, high temperature environment relevant to air-breathing propulsion systems.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.02.01 2008, 2010	High-Mach Fan Stability and Performance Modelling	HYP.2.02.P01 HYP.2.02.01	Analyze the RTA fan stage data and evaluate the ability of the state-of-the-art CFD to predict the performance and stall margin of the RTA fan at design and far-off design operating conditions. Assess the ability of SOA models to predict stability margin over a wide range of operation with both a uniform inlet (2007) and distorted inlet (2008, 2009). Inlet distortions resulting from the TBCC dual integrated inlet study in Milestone HYP.2.02.P3 will be utilized.	Document SOA stability models ability to predict stability for highly integrated Mach 4 fan stage with uniform and distorted inlet conditions. Quantify uncertainty in SOA fan performance models. Validated models if data and models agree within 5%. Complete highly integrated inlet/fan stage stability models. Fan aerodynamic operability range increased by a factor of 3. Archive results in technical journal. Publish database in electronic format.	Aerodynamic Stability model and uncertainty level Documented. Documentation of differences between calculation and experiment. Document SOA stability models ability to predict stability for highly integrated Mach 4 fan stage with uniform and distorted inlet conditions. Guidelines for using/improving aerodynamic stability model.
HYP.1.02.18 2007 2011	Test Media Effects		Improve SOA for predicting the effect of vitiation on test results, acquired in combustion-heated test facilities.	Using existing models and codes, establish SOA for predicting test-gas contaminant effects for; (1) ignition and flame holding, and (2) turbulent flame propagation by conducting two "unit" test/analytic problems. Improve capability for prediction of extinction limit to within 10% (based on fuel equivalence ratio) and prediction of thrust to within 5% of measured value (\pm experimental uncertainty).	Developed phenomenological and subgrid scale models, modified RANS and LES codes, and documentation defining results of work and experimental databases.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.02.22 2008 2011	Improve modeling and codes for turbulent reacting flows		Use existing and new (HYP1.02.18) experimental databases to improve phenomenological turbulence and subgrid scale models for use in: (1) RANS codes, (2) hybrid RANS/LES, (3) LES/PDF, and (4) PDF codes to simulate turbulent high-speed reacting flows. Also improve the accuracy/efficiency of algorithms used in codes.	Incorporate new/improved phenomenological models, hybrid RANS/LES enhancements and scalar PDF modeling into VULCAN. Complete development of LES/PDF method and compressible Lagrangian PDF method and incorporate into codes. Quantify accuracy of codes by assessing two "unit" turbulent-combustion problems - one addressing hydrogen fuel and the one addressing hydrocarbon fuel. Compare results against the following measured values and accuracy goals (relative to measurement \pm measurement uncertainty): velocity $\pm 5\%$, species $\pm 5\%$ mass percent, temperature ± 25 K, wall pressure $\pm 5\%$.	Algorithms (subroutine format), new and enhanced codes and associated documentation will be delivered. Results will be published in journal articles.
HYP.1.02.38 2009 2011	Hypervelocity Combustor Design and Evaluation		Design, test and evaluate the performance of a hypervelocity scramjet combustor operating on hydrogen fuel at stoichiometric levels.	1) Establish consensus SOA performance level, utilizing existing hypervelocity combustor data (obtained from pulsed facility, true-total-enthalpy testing). 2) Conduct design-study to yield a Mach-15 combustor design and test at Mach 15 conditions in HyPULSE, yielding a 20% improvement in performance compared to established SOA.	Test results and analysis of data (inclusive of consensus state-of-the-art), as well as relevant design algorithms, will be archived both electronically and in reports.
HYP.1.02.41 2008 2010	Develop high speed ignition and flameholding modeling capability		Improve SOA for ignition and flame-holding modeling via improved chemical kinetics models, incorporation of models into combustion codes, and validation of codes by comparison with experimental data.	Establish the SOA for computationally tractable mechanisms for hydrogen and hydrocarbon (HC) fuels. Develop and validate reduced, computationally tractable chemical mechanisms that yield (within 10%) the results (e.g., key species production) of the complete kinetics mechanism. Combustion codes utilizing reduced kinetics models will be used to (1) predict the ignition and flameholding characteristics of the OSD experiment with a goal of predicting blowoff limits within 10% of experimental values (\pm experimental uncertainty), and (2) predict the flame stability margins in a hyperburner environment (CE5 experiment) with a goal of predicting to within 10% of experimental values (\pm experimental uncertainty.)	Documented reduced kinetic mechanisms and resultant subroutines will be incorporated into RANS, RANS/LES, LES/PDF and PDF codes. Kinetics mechanisms, test results, and associated analyses will be documented in journal articles.
HYP.1.02.48 2011	OJB experiments for validation of reduced HC kinetics models		Design and conduct OJB experiments using HC fuels (fuel mixtures, blends, with and without additives). Validate combustion codes (using reduced kinetics mechanisms) via prediction of OJB extinction limits.	Design and conduct OJB experiments using HC fuels (fuel mixtures, blends, with and without additives). Validate combustion codes (using reduced kinetics mechanisms) via prediction of OJB extinction limits to within 10% (of blowoff strain rates over a range of equivalence ratios for various HC fuels).	Documentation of OJB experimental data, analyses, and combustion code validation results.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.02.49 2007 2011	Three-Dimensional Inlet Modeling	pre-Hyp'fy06 4.01.02? 2.02.19?	CFD analyses will be conducted on 3-D inlet designs in concert with appropriate testing. Both the RATTILRS inlet configuration and selected dual flow paths will be analyzed over the Mach, alpha and beta ranges.	Document SOA methods to predict 3D integrated inlet flows. Perform 3-D RANS calculations of selected RATTILRS inlet configurations and dual-flowpath inlets across the Mach, alpha and beta ranges tested. Models are deemed validated if mass flow, pressure recovery, and distortion values are shown to be within $\pm 2\%$ of experimental measurement (\pm experimental uncertainty.)	Document SOA methods to predict 3D integrated inlet flows. 3-D RANS calculations on experimental forebody-inlet geometries including inlet boundary-layer bleed modeling. Documentation of differences between calculation and experiment. Guidelines for performing inlet performance calculations.
HYP.1.02.50 2007 2010	Three-Dimensional Nozzle Modeling	1.02.24 1.02.35 1.03.03 1.03.04 1.03.05 1.03.15 1.03.23 2.02.22 2.02.23 2.03.08 2.03.10 2.03.11 2.03.12 3.02.01 3.02.23	Document SOA methods to predict 3-D integrated nozzle flows. High Mach number nozzles are characterized by complex internal and external flow features including boundary layer separation, relaminarization, real gas effects, and compressible mixing and heat transfer mechanisms.	Perform 3-D RANS Calculations of selected integrated nozzle configuration at transonic, supersonic, and hypersonic conditions over the relevant Mach and NPR range. calculated flow coefficients (if applicable), gross thrust, boat-tail drag, and net thrust coefficients are within 1/4% of experimental values, or within the experimental uncertainty, whichever is larger.	3-D real-gas RANS calculations on experimental integrated nozzle geometries including external flow effects. Documentation of differences between calculation and experiment. Guidelines for performing accurate nozzle performance calculations.
HYP.1.02.52 2007	Fuel Characterization Modeling		Conduct OJB flame extinction experiments to characterize the ultimate flame strength of: JP fuels; surrogate mixtures of gaseous hydrocarbons that mimic thermally stressed JP-fuels; and candidate fuel additives and blends that enhance high-speed ignition, flame-holding, and reduce coking at high heating rates.	Establish flame strengths for JP fuels. The characterizations of JP-7 and other JP-fuels, with and without additives, will be expressed in terms of fundamental physical-chemical properties. Develop surrogates for chemically-complex thermally-stressed (cracked) JP-7. The goal is to match heat release, flame strength, and molecular weight to within 10% for each quantity.	Documentation of experimental flame strength results and other analytical characterizations of the combustion of neat JP fuels (including JP-7), JP fuels with candidate additives, thermally stressed JP fuels, representative surrogates, and hydrogen. Quantification of gaseous surrogate compositions and other relevant properties for thermally stressed JP-7, for use on FRESH-FX (Flight #2 & #6) hydrocarbon-fueled Scramjet Flight Experiments.
HYP.1.02.C02 2009 2011	IRS-RBCC Ignition/ Flameholding & propagation models	HYP.1.02.12 HYP.1.02.11 HYP.1.02.06 HYP.1.02.10 HYP.1.02.35	Assess and document SOA IRS-RBCC ignition/ flameholding & propagation models. Utilizing modified-existing rigs as testbeds, parametrically explore ignition, flameholding, and flame-propagation effects for use in multiple fuel options. Systematic variations in fuel-staging location, turbulent mixing schemes, and flameholding geometries will be used to compare combustion CFD methods for subsequent methods improvement & validation.	Document SOA IRS Ignition/Flameholding & propagation models. Thermal throat established, and maintained in ramjet stream, with a 90% combustion efficiency for the range of Mach 0.5 to 3.0 conditions.	Documentation of SOA IRS Ignition/Flameholding & propagation models to serve as baseline. Practical dual-mode ramjet burner design that is operable from Mach 0.5 to 3.0. Documentation of design procedures and parametric database.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.02.C03 2010	Unsteady/ pulsed combustion for RBCC Ejector Operation		Analytical methods will be employed to better understand unsteady forced response of multi-stream flows. Multi-disciplinary computational flow and structures modeling will be used in conjunction with wall-interaction models (shock/BL and heat transfer) to investigate potential performance enhancements (unsteady versus steady state).	Analytically demonstrate a 10% improvement in low speed ejector-ramjet performance for an unsteady process over the analogous steady process. Analytically demonstrate a 5% improvement in rocket-mode performance for an unsteady process over the analogous steady process.	Documentation of improved analysis methods, designs, and performance of unsteady ejector, and fuel injection processes.
HYP.1.02.C09 2009 Q4 2011 Q4	High-Mach Turbomachinery Aeromechanics Modelling	HYP.1.02.04 HYP.2.02.25 HYP.2.02.P01	Document SOA methods to predict aeromechanic stability. Experimental turbomachinery aeromechanical validation of stability models utilizing fan rig test data.	Document SOA methods to predict aeromechanic stability. Quantify uncertainty in SOA fan aeromechanic stability CFD tools by comparing codes to data. Verification/Validation of code if fan tip movement and stability limits are predicted within 10-20%. Develop non-linear models if required and document. Fan aerodynamic/ aeromechanic stability range increased by a factor of 3.	Document SOA methods to predict aeromechanic stability. Quantify uncertainty in SOA fan aeromechanic stability CFD tools by comparing codes to data. Aeromechanic Stability model and uncertainty level documented. Documentation of differences between calculation and experiment. Guidelines and procedure to correlate blade tip deflections (via casing measurements w/ light probes) to blade strains documented. Develop nonlinear methods /models if required and validate/ document.

HYP.1.03—Fundamental Aerodynamics, Aerothermodynamics, Plasma Methods

The objective of this research is in direct support of developing and validating predictive tools to enable NASA critical missions such as HRRLS and HMMES. Modern design tools for engineering level hypersonic studies rely on fast low-fidelity methods to carry out parametric and configuration optimization studies. The major modern improvement to these methods is the use of Euler and full Navier-Stokes solutions to anchor the solutions generated using the low-fidelity methods. To summarize, the fidelity of the aero and aerothermodynamics databases is anchored using a limited number of high-fidelity CFD solutions that capture the complex physical processes experienced by a vehicle flying at hypersonic speeds, see Figure 10. Direct numerical simulation (DNS) of turbulence, transition and other complex gas-surface interactions are not feasible for configuration design with today's computers and requires physics-based models to simulate these processes. Experiments are needed to guide the development of these models and to provide validation of the numerical tools. Thus, the

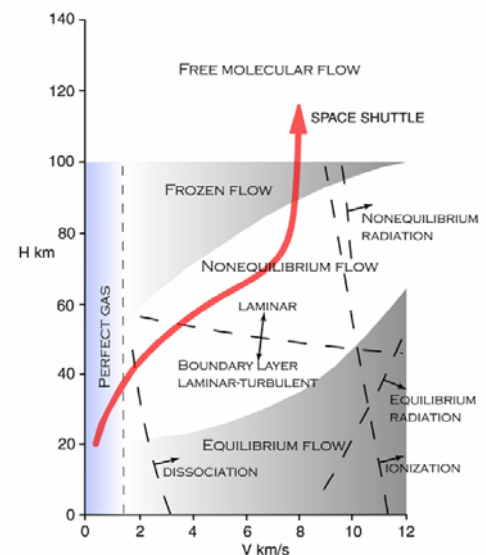


Figure 10. Illustration of physical processes encountered by a vehicle in the hypersonic regime. Typical Space Shuttle flight path is shown in red.

program proposed has three major components: 1) development of advanced simulation tools; 2) development of physics-based models; and 3) establishment of experimental databases. The proposed effort lays the foundation for the efficient use of high-fidelity tools in design and optimization, but work on this area is beyond the current 5-years horizon. The milestones listed under this effort are considered critical milestones, but represent only a subset of the total work planned. In addition, plans are underway to collaborate with the Air Force Research Laboratory (AFRL) in many areas to evaluate the strengths and weaknesses of various simulation approaches and to assess the SOA. Model problems will be jointly developed to serve as a reference line for current technology. Efforts will be augmented through targeted NRA and SBIR activities.

Development of Advanced Simulation Tools.—Under this effort current simulation capabilities will be enhanced and new capabilities will be developed. The milestones specific to this area are:

- HYP.1.03.63 establish SOA baseline for simulation tools
- HYP.1.03.11 higher order space/time methods
- HYP.1.03.C06 auto grid adaptation with higher order methods
- HYP.1.03.45 higher order methods for DNS of non-equilibrium flows
- HYP.1.03.48 error estimation and control

These milestones will enable increased spatial and time accuracy, increased geometrical complexity, grid adaptation, increased physical-processes complexity, uncertainty quantification, and error control. To achieve these goals modern software tools and practices will be applied to implement new algorithms on massively parallel computer architectures. These milestones enable capabilities that will aid both the HRRLS and HMMES missions.

The complex physical phenomenon and the wide range of spatial and time scales present in flows containing gas-surface interactions, entropy and shear layers, shock waves, real-gas effects, and turbulence and transition make the development of efficient and accurate numerical simulation extremely challenging. For enhanced spatial accuracy, high-order algorithms for both structured and unstructured grids, such as low-dissipation, discontinuous Galerkin, and spectral-difference algorithms, will be tested on relevant model problems in order to evaluate their relative strengths and weaknesses. The accurate prediction of the onset of boundary layer transition is critical for the evaluation of heating and the design of thermal protection systems. Typical of work to be done in this important area is the development of higher order methods to compute transitional flow by DNS. This work will provide insight for the development of transition models.

Time-accuracy is important for the accurate prediction of the motion of coupled multiple bodies, unsteady fluid dynamic effects, and full flight simulation where 6-degree of freedom equations are solved simultaneously with the governing flow equations. These effects can produce such behavior as dynamic instability (e.g., in capsules in supersonic flow) and proximity aerodynamic interference in cases of closely spaced bodies in relative motion (e.g., during staging). High-order Runge-Kutta and implicit dual time-stepping methods will be tested for their effectiveness in these problems.

Uncertainty quantification is needed as a first step towards quantifying and managing risk. Sources of uncertainty include model equations, model parameters, geometric representation, flow environment, boundary conditions, and numerical errors. Adjoint methods will be developed to provide a means to detect and control sources of error, and relate them to engineering outputs of interest such as aerothermodynamic heating and drag. Furthermore, techniques for grid adaptation to capture essential flow features will be developed using adjoint methods as an improvement to heuristic methods. Other

more general Monte-Carlo methods will also be developed for sources of uncertainty that are not amenable to analytic approaches.

Development of Physics-Based Models.—Physical modeling of non-equilibrium chemistry, surface catalytic effects, turbulence, transition and radiation will require developing and testing algorithms for the expanded equation sets. The milestones specific to this area are:

- HYP.1.03.C01 turbulence and transition database
- HYP.1.03.21 gas-surface interactions including chemistry
- HYP.1.03.43 simulation of transition onset
- HYP.1.03.32 experiments on transition and turbulence with ablation

DNS and experiments will be used to gain insight in the development of chemistry, radiation and turbulence models that are needed to reduce the computational effort. Gas-surface-ablation interactions play a critical role in the design of thermal protection systems. Ablation experiments are proposed using different coatings of phosphor that will sublime during the test run. It is expected that the sublimation will lower heat transfer to the model surface, and by measuring differences of the coated phosphor layer, the impact of sublimation on the heat transfer will be quantified. These measurements will be used in the development and evaluation of hypersonic ablation physics-based models. DNS will be used to study the physics of boundary layer interactions with ablating and/or reacting surfaces. The goal is to develop near-wall models that can be coupled to LES or a hybrid (RANS/LES) simulation methodology. In addition, fully generalized models for surface catalysis will be developed and incorporated into CFD codes. In the area of boundary layer transition, modeling efforts will target hypersonic-specific enhancements to SOA prediction tools based on stability theory and/or parabolized stability equations, such as the Langley Stability and Transition Analysis Codes, as well as the application of those enhanced tools to selected hypersonic configurations that cover the range of transition issues of airbreathers, CEV, and planetary probes including the HRRLS and HMMES missions (e.g., slender to highly blunt models over a range of angle of attack and surface temperature).

Establishment of Experimental Databases.—Experiments and improved experimental techniques are proposed to develop better understanding of high-speed flows, and provide data that can be used to validate and guide the development of simulation tools. The milestones specific to this area are:

- HYP.1.03.C01 SOA turbulence and transition database
- HYP.1.03.31 experiments on transition and turbulence
- HYP.1.03.32 experiments on transition and turbulence with ablation

Under the first milestone, a SOA database of existing experimental data on transition and turbulence will be compiled with the purpose of assessing the effectiveness of transition and turbulence models. We expect significant involvement of academia, industry, DoD and NASA in this effort. Under the second milestone, new turbulence, transition and heat transfer data will be obtained in wind tunnels as well as in flight experiments, such as the Hy-BoLT (NASA) and the Fundamental RESearch from Hypersonic Flight Experimentation ((FRESH-Fx) USAF/NASA/Australia). Also under this effort, transition stabilization techniques using microwave-generated plasmas will be developed. The plasma studies will be validated using existing and new experimental test results of flow control in which plasma actuators achieve drag and/or thermal load reduction under high-speed flight conditions. Under the last milestone, tests will be conducted to obtain experimental datasets on transition and turbulence in the presence of ablating materials. These ablating tests will be conducted in the Langley 31-Inch Mach 10 Tunnel and will include flow visualization using planar laser-induced fluorescence and heat transfer measurements

using global IR. This study will complement work being done for modeling ablation in NASA's CEV program.

Additional work, beyond these milestones, will investigate transition phenomena induced by isolated and distributed surface roughness. Successful implementation will provide a practical means of obtaining heating measurements and transition criteria under flight-relevant conditions in the NASA Ames Research Center (ARC) Hypervelocity Free-Flight Aerodynamic Facility. Other studies will assess the effectiveness of transpiration cooling on sharp leading edges and nose-tips for high L/D hypersonic vehicles and the use of transpirants that undergo endothermic reactions to improve thermal protection. The interest in transpiration cooling is that it enables vehicles with sharp leading edges without relying on a materials solution. Such re-entry vehicles can attain large cross-ranges, reducing re-entry delay times from high-inclination orbits.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.03.C01 2009 Q4	Assess Turbulence & Transition Modeling for Hypersonic Flows	HYP.1.03.01-06	Define turbulence and transition criteria using existing SOA data for hypersonic flows. Establish standards, uncertainty measures, portable frameworks, and sampling techniques useable by the general community for a variety of diverse means.	Way point--no metric available	FY08: Create database with acreage heating data. Provide assessment of RANS turbulence modeling best practices. Grow database to include after-body, ablation and shock-bl interactions. Provide assessment of transition criterion and of LES methods wrt experimental data. FY09: Grow database to include further transition and hypersonic turbulent heating. Updated assessment of turbulence RANS/LES best practices. FY10: Final recommendations on best practices, expert representation from NASA, academia and industry.
HYP.1.03.11 2011 Q4	Develop Higher Order Space/ Time Simulation Capability for Non- Equilibrium Hypersonic Flows		Develop higher order unstructured space/time capability for unsteady 3D thermochemical non-equilibrium RANS solvers. Simulate thermal environment fluctuations to support LES calculations.	FY10: Develop high-order 3D unstructured grid solver for non-equilibrium hypersonic flows for generalized thermal and chemical non-equilibrium gas mixtures. FY11: Demonstrate efficiency on large scale (massively parallel) LES computations for high-speed, real-gas flows that exceed current structured grid solver capabilities by a factor of 10, while allowing simulation of complex geometries and grid adaptation that are intractable with structured grid methods. SOA baseline defined by HYP.1.03.63.	Higher order space/time-accurate non-equilibrium CFD code for LES.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.03.C06 2011 Q4	Auto Grid-Morph Unstructured CFD Adaptability	HYP.1.03.23-31	Develop higher order numerical discretization methods (both temporal & spatial) and morphing of unstructured meshes based on adjoint method for 3D hypersonic flow with finite rate chemistry. Validate CFD engineering methods from previous milestones by employing new mesh techniques against progressively complex experimental model tests. Provide methods and model data in standards for use by general community.	FY08: Demonstrate unstructured grid deformation with factor of 10 improvement within 3D aeroelastic deformation and design. FY09: Demonstrate factor of 50 reduction in total computer cost to given level of discretization with adaptation for realistic 3D computation. FY11: Demonstrate a factor of 10 reduction in computational cost for given accuracy by using high-order time-space discretizations in an unsteady simulation. SOA baseline defined by HYP.1.03.63.	Unstructured grid CFD code with grid morphing capability for non-equilibrium flows.
HYP.1.03.21 2010 Q4	Develop Gas Surface Interaction Models for Laminar and Turbulent Flows	HYP.1.03.15	Fully generalized models for surface catalysis (promoting chemical reactions) and momentum and energy accommodation coefficients (slip conditions) will be added to CFD codes. Choice of thermal protection system is critically dependent on these effects for hypersonic entry conditions.	FY09: Add heterogeneous surface recombination boundary conditions to CFD codes. FY10: Surface chemistry model in CFD, including oxidation, nitridation, and sublimation, for Earth atmospheres. Updates to species densities, momentum, and energy equations. Show 30% improvement over FY06 capability. SOA baseline defined by HYP.1.03.63.	CFD code with improved surface interaction models.
HYP.1.03.31 2009 Q3	Set of Experimental Data on Hypersonic Transition & Turbulence		Experimental data is crucial for verification and validation of any design tool. Data on turbulence & transition at hypersonic speeds is extremely rare and is crucial for progress in this regime.	FY07: Transition test on a cone. Show mechanical systems function per specs and calibrated, obtain low noise wire data.--- Generate microwave plasmas up to 50 kHz for flow control and "trip" applications. FY08: Obtain calibrated mean & fluctuation turbulent bl profiles, surface temperature pressure & thermo graphic data for sharp & blunt cone with smooth & rough surface. FY09: Duplicate FY08 study in quiet tunnel.--- Demonstrate stabilization of transition using high frequency microwave plasmas at M= 6 by driving natural (first mode) instabilities in bl. Compare with predictions, prediction & test technique validated if within 5 % of measured parameters. SOA baseline defined by HYP.1.03.63 and HYP.1.03.C01.	Document techniques for transition stabilization and obtain datasets on turbulence and transition and heat transfer. Experimental data sets with quantifiable error bars documenting transition physics with natural and forced transition under various flow conditions. Experimental data sets with quantifiable error bars detailing the mean and fluctuating flow in turbulent bl with quantifiable error bars.
HYP.1.03.32 2011 Q1	Set of Experimental Data on Hypersonic Transition & Turbulence with Ablating Materials		Obtain experimental dataset on transition & turbulence in the presence of ablating materials.	FY08: Design, test & evaluate ablating-blowing test models in vacuum chamber. FY09: Test & evaluate ablating-blowing test models in hypersonic wind tunnel. FY10: Test & develop validation database for turbulence & transition study. FY11: Analyze & report study for validation turbulence & transition with LTA materials & blowing. Compare with predictions, prediction and test technique validated if within 5 % on measured parameters.	Datasets for turbulence and transition with ablation effects.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.03.43 2010 Q3	Validate Parabolized Stability Equation For Hypersonic Transition		Analysis methods for prediction of boundary layer transition onset.	FY08: Incorporate transition prediction onset into SOA CFD codes. FY10: Validate transition onset prediction against X-43A, Hy-BoLT, FRESH-Fx and other available flight data, demonstrating 25% reduction in prediction uncertainty relative to SOA engineering methods. SOA baseline defined by HYP.1.03.C01.	CFD code with transition prediction onset.
HYP.1.03.45 2010 Q4	DNS of Turbulent Transition of Non- equilibrium Hypersonic Boundary Layer		Develop high-order methods for DNS of non- equilibrium flows.	FY08: Develop DNS capability for computing transition of non- equilibrium hypersonic bl. FY10: Demonstrate DNS capability for BLT and provide detailed data for non-equilibrium flows. Validate data against best available experiments. Compare with predictions, prediction & test technique validated if within 5 % on measured parameters. SOA baseline defined by HYP.1.03.63 and HYP.1.03.C01.	CFD code for DNS computation of non-equilibrium flows.
HYP.1.03.48 2011 Q2	Hypersonic Solutions on Adaptive Unstructured Grid to User Prescribed Error Tolerance	HYP.1.03.C03 HYP.1.03.C06	Integrate error estimation and mesh adaptivity techniques for steady and unsteady flows into existing hypersonic flow solvers.	FY08: Demonstrate mesh adaptivity for error control. FY11: Demonstrate factor of 100 reduction in total time to given level of truncation error for hypersonic multi-species, multi- temperature, reacting gas model gas for unsteady flows. SOA baseline defined by HYP.1.03.63.	CFD code capable of adapting grid to control specified error
HYP.1.03.63 2007 Q2	Define Baseline Cases for Simulation Assessment		Define minimum of three hypersonic configurations that will be used to track progress in simulation capabilities. Compute reference solutions with existing technology.	Way point—no metric available	Benchmark existing simulation tools on web site for tracking progress in CFD methods. Publish results, geometry, grids, analysis of results on web site for tracking future progress in CFD methods.

HYP.1.04—Measurement and Experimental Techniques

A variety of optical and conventional measurement techniques have been developed to study fluid mechanics and combustion. However, the extreme conditions—such as high temperatures—encountered in hypersonic flows present a challenge for many of these techniques. Thus, current capabilities for flow measurement in hypersonic test facilities and flight are relatively modest and limited, for the most part, to Schlieren flow visualization and intrusive pitot-static and hot-wire probes. Several advanced measurement techniques will be extended to the hypersonics regime as part of this project.

A key theme common to these needed experimental capabilities is that they contribute directly to validating and developing physics-based CFD and other modeling codes. These modeling codes are critical to development of predictive capabilities for design of HRRLS and HMMES, due to the high uncertainty in these flight regimes. For new and existing measurement techniques, uncertainty bounds that include effects from the unique hypersonic flight

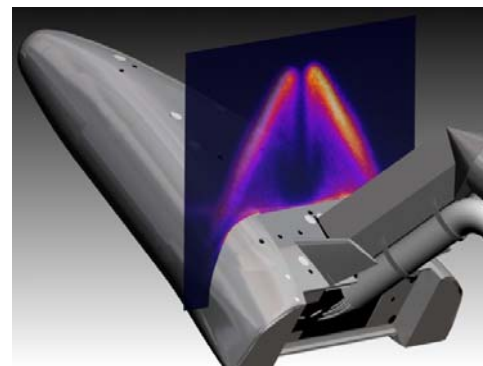


Figure 11. Planar laser-induced fluorescence (PLIF) visualization of the X-33 wake flow at NASA in 2005.

environment must be quantified to allow system level analyses. The proposed level 1 approach combines a significant allocation of resources towards flowfield measurements with select key elements to advance and support hypersonic flight testing and materials development. The development efforts in this topic area are divided into two major sub-topics, the development of advanced instrumentation and experimental techniques for propulsion and hypersonic ground test and flight.

Instrumentation

Shock Position Sensor (HYP.1.04.63).— The development of high temporal and spatial resolution shock position sensing techniques is required in order to optimize the hypersonic propulsion system inlet geometry which ultimately affects the propulsion system performance and stability of HRRLS. Shock standoff distances are also applicable to HMMES due to the correlation of standoff distance to heat transfer of blunt bodies. Shock position sensing will be valuable in ground tests of candidate inlet geometries and may be adaptable into flight sensor systems.

Two strategies will be used in the development of an optical refraction based shock position sensor. The first approach will use a scanning pencil beam to detect the shock location in an inlet. A small diameter laser beam will be mechanically scanned in a line across the inlet. A linear array detector on the opposite wall of the inlet will be used to record the beam position as it is scanned. When the beam crosses a shock the pencil beam is refracted (by the density gradient caused by the shock) and split into two beams. The linear array detector will record the location and time of the beam splitting event, which indicates the shock location in the inlet.

The second approach for sensing the shock position is to use a collimated light sheet to traverse the inlet and impinge on the far wall. The width of the light sheet is designed to exceed the range of shock positions within the inlet. The collimated sheet acts as a shadowgraph. Any disturbance caused by the shock will refract the collimated rays of laser light in the sheet, which will produce a shadow in the image of the light sheet on the far wall of the inlet. A high speed CMOS sensors will be used to image the light from the light sheet. The CMOS sensor has 1280 pixels and is capable of operating up to several kHz. The images obtained from the CMOS sensor will be processed in real time to provide the shock position to high temporal and spatial resolution. If the light sheet width is set to 50 mm, then the detected resolution of the shock position is approximately $50 \text{ mm}/1280 \text{ pixels} = 40 \text{ microns}$, assuming the center of the shock's shadow can be estimated to within 1 pixel. Both shock position sensing techniques will be tested in a 15x15 cm supersonic wind tunnel. The 15x15 cm tunnel at GRC has optical access on three sides, and will provide the necessary test bed for both techniques.

Perform Fundamental Measurements in Axisymmetric Reacting Jet [Co-Funded by DoD]—CARS/Rayleigh (HYP.1.04.39).—Today's computational fluid dynamics (CFD) codes cannot accurately predict ignition and flameholding in scramjet engines. To overcome this limitation, scramjet engines are designed conservatively with high-drag flame-holding fuel injectors. To improve the computational capability, which may allow more efficient, low-drag fuel injectors a new class of turbulence models is required. An existing collaborative project aims to obtain a set of data that will allow researchers at North Carolina State University, George Washington University, and NASA to develop improved turbulence models that will improve this predictive capability. This project is supported by NASA and the Office of the Secretary of Defense, Defense Test Resource Management Center's (DTRMC) Test and Evaluation/ Science and Technology (T&E/S&T) program through 2008. The experimental data acquired for this project will be obtained using NASA's CARS/Rayleigh system. The data set will include temperature, velocity, density, and composition measurements, their distributions, fluctuations, and cross-correlations, in a reacting axisymmetric jet. This jet can contain

excess hydrogen or hydrocarbon species to allow simulation of hydrogen or hydrocarbon scramjet engines. This project enables improved prediction of many propulsion flowfields.

Temperature Sensitive Paint (TSP) (HYP.1.04.36).— The development of high spatial and temporal resolution temperature sensing techniques are needed to optimize high temperature materials for hypersonic structural components and propulsion systems. While infrared techniques have provided valuable surface temperature data, these techniques can yield less than optimal measurements when contaminants such as engine exhaust are in the flow path. Viewing in test facilities is also limited due to the lack of optical access or the need for special windows for IR transmission. The use of temperature sensitive coatings has been shown to be productive in these cases.

Techniques to increase material compatibility properties and the accuracy of TSP measurements will be investigated and developed. The binders used in many TSPs are ceramic and have a high thermal resistance. For many applications, the thermal conductivity must be raised to more closely match metals or CMC materials. In the case of CMC materials, the thermographic phosphor sensors may be embedded in the composites as an integral sensor that can be optically scanned or imaged. By using an optically transparent material, high temperature heat flux sensors can be developed using one or more phosphor sensors on opposite sides of the transparent material.

The accuracy of the TSP technique is usually compromised by stray light emission from flames or high temperature materials or contaminants. Several techniques to boost the signal to noise ratio of this technique will be investigated which include pulsed laser rastering of the excitation light and investigating the new very short wavelength UV light emitting diodes as potential excitation sources. The use of multi-spectral phosphors will be explored for high temperature use as a compensation for high black body radiation or flame signals. These techniques will be demonstrated in the Quick Access Rocket Exhaust or the Mach 0.3 burner rigs.

Experimental Techniques

Test Techniques for Large Structures (HYP.1.04.C06).— Advanced instrumentation and test techniques for large structures, are required to perform many functions in the area of structural testing. Ground Vibration Testing (GVT) is one required test technique. Currently there is no capability to obtain GVT information under the correct aero and aerothermal loading conditions on the large structures required for the HRRLS or HMMES. Technique development would start with small structures, and would include prototype strain, acceleration, temperature, heat flux, and surface deflection instrumentation for application to high-temperature testing of hypersonic materials and large-scale hot-structure components. The metric for this technique is to measure mode shape and frequency content to within 15% of engineering predictions. The intent is that these techniques will be used for large-scale hot structures but validation for such complex systems will require an outside partnership.

Nitric Oxide (NO) Planar Laser-Induced Fluorescence (PLIF) System for Measurement of Static Temperature (HYP.1.04.38) and Construction and Installation of “Production” PLIF Flow Imaging System for Hypersonic Facility Complex (HYP.1.04.37).— The current NASA capability of NO PLIF is limited to off-body flow measurements, including velocity measurements, in wind tunnel tests (Figure 11). Measuring the gas temperature field is also a very important parameter that can be compared with CFD codes for validating models imbedded in those codes. Such models may predict nearly the same velocity field while predicting significantly different temperature fields in some applications, for example in laminar hypersonic boundary layers. Thus, it is important to measure both velocity and temperature in hypersonic flowfields when evaluating different predictive methods for hypersonic flow. Another reason the static gas temperature is important to measure is because

phenomena such as ignition and flameholding in scramjet engines is very sensitive to temperature—the conditions of the experiments should be precisely known. The ability to measure temperature with NO PLIF has been demonstrated at a few universities and at least one large research laboratory. However, the capability has not been implemented at NASA despite the advantages it would provide. The hardware required to perform this task is already in use within NASA. Software modifications are required, and a series of careful calibration experiments must be performed in order to measure temperature and to quantify the uncertainty of the measurement.

The NO PLIF technique has recently been used at NASA to visualize and quantify the trajectory of Reaction Control System (RCS) Jets for the CEV, for determining criteria for transition to turbulence in simulated shuttle orbiter wing-breaches for the Return to Flight (RTF) program, for visualizing hypersonic wake flowfields in various planetary entry configurations like Mars Science Laboratory (MSL) and for visualizing cavity flows with military applications to store separation. These measurements have been performed with a “development” PLIF system which moves from tunnel to tunnel, and which is constantly being improved. There is a need for a “production” PLIF system to be permanently installed in the 31” Mach 10 wind tunnel so that it is available for routine use. While most of the equipment required is already present within NASA, the system needs to be assembled, tested, and implement in the tunnel to provide a day-to-day measurement capability not currently available. A significant advantage to having a 2nd operating PLIF system is that it can be combined with the 1st system to eventually measure temperature in turbulent flowfields.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.04.64 2007 Q2	Gain level 1 SOA baseline consensus to evaluate metrics against		Document the SOA hypersonic experimental capabilities at level 1. Identify baselines to measure progress against for measurement techniques, and test environments.	Way point--no metric available	Technical Memorandum and/or journal article reporting level 1 SOA
HYP.1.04.63 2008 Q4	Optical shock position sensor development	HYP.1.04.08 HYP.1.04.09 HYP.2.05.07	Apply CMOS cameras and fiber optically coupled laser light sheet for single sided optical access technique for high temporal/high spatial shock position sensing	Minimum of 1 kHz temporal response. Spatial resolution of 2 mm	Fiber optically coupled shock position sensor system and report
HYP.1.04.37 2009 Q2	Construction and installation of "production" PLIF flow imaging system for Hypersonic Facility Complex		An NO PLIF imaging system will be delivered that can be run by the tunnel operators; will be delivered to the Hypersonic Facilities Complex	Way point--no metric available	Capability of performing PLIF flow visualization on demand with minimally trained technicians. Delivery of measurement system and associated operations documentation.
HYP.1.04.39 2008 Q1	Perform fundamental measurements in axisymmetric reacting jet [co-funded by DoD]		CARS/Rayleigh will be used to simultaneously measure T, rho, u, v, w, mole fractions in a combustng axisymmetric jet in Langley's Direct Connect Supersonic Combustion Test Facility	Measurement uncertainties of all parameters of 4% of measured property or better.	Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.1.04.36 2009 Q2	Development of TSP for use in hypersonic environment		Develop TSP coatings for high temperature operation	TSP: Increase accuracy by 2x, operate up to 650 °C	Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.1.04.19 2009 Q4	Non-intrusive inlet mass capture measurement technique		Measure density, duct area, and velocity simultaneously, probably using diode lasers in laboratory duct flow.	Provide time accurate inlet mass flux measurement $\pm 10\%$ accurate in laboratory environment	Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.1.04.C06 2009 Q1	Adv. Instrumentation and test techniques for large structures	HYP.1.04.06	Advanced instrumentation system for piecewise testing of large structural test articles. Includes prototype strain, acceleration, temperature, heat flux, and surface deflection instrumentation for application to high-temperature testing of hypersonic materials and large-scale hot-structure components. Validated instrumentation required for model validation and analysis correlation.	Demonstrate ground vibration test techniques for hypersonic vehicle a to within 15% (mode shape and frequency) engineering predictions; Demonstrate GPS-based deflection measurement system accuracy on simple structure to within 0.10 in.; Develop high heat flux sensors and associated calibration; Quantify the uncertainty of heat flux calibration to achieve at least an order of magnitude higher accuracy.	Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.1.04.34 2009 Q4	Implement required facility enhancements to provide the relevant environment for experimental validation of inlet/shock train/isolator measurements		Provide required modifications to inlet/shock train/isolator test facilities, including integration of advanced diagnostics, to provide the relevant environment for proposed experimental activities and improve the fidelity of measured data.	Complete design and facility upgrades for focused experiments which will enable calibration/ refinement of computational tools and ultimately provide a reduction of at least 50% on the error band for resultant performance evaluation (i.e., recovery/ pressure rise, shock location, flow rate, stability margin and distortion)	Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.1.04.38 2010 Q2	NO PLIF system for measurement of static temperature	HYP.1.04.37	NO PLIF system upgrade to measure gas temperature in hypersonic wind tunnels	Instantaneous flow static temperature measurement accuracy of 7% or better (currently this capability does not exist).	Upgraded NO PLIF system. Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results

HYP.2.01—Materials and Structures

Level 2 objectives focus on developing structural design and analysis tools (Figure 8) that will enhance level 4 PB-MDAO capabilities. As previously discussed, the level 1 fundamental “building blocks” (HYP.1.01.C29, C36, C28, and C37) support level 2 design and analysis tools development and advanced structural concept validation for future hypersonic airframe, propulsion, and propellant tank applications. In addition to an initial baseline effort, against which M&S technology advancements will be compared, the level 2 effort, as shown in the roadmap below (Figure 12) is focused on the following four themes:

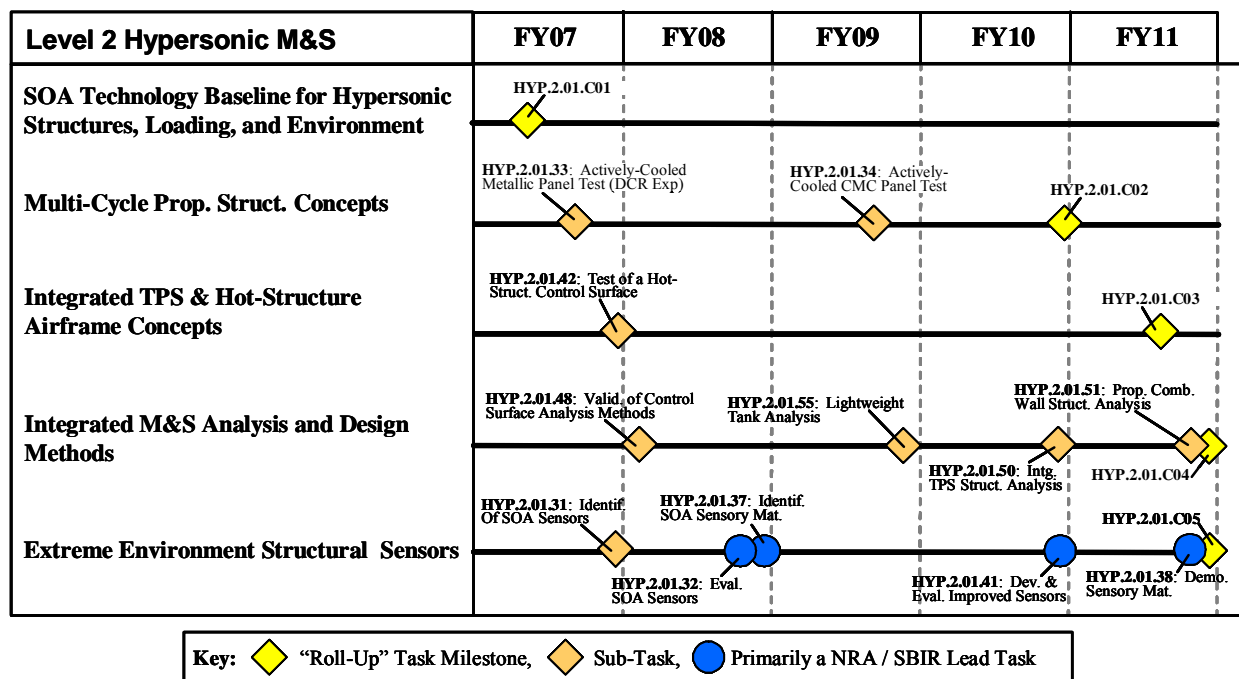


Figure 12. M&S Level 2 Milestone Roadmap.

Multi-Cycle Propulsion Structural Concepts.—A focused effort to develop structural concepts that reduce inlet and liner weight for prototypical TSTO HRRLS TBCC and Scramjet propulsion concepts will be pursued. High heat flux within a Scramjet combustor requires actively-cooled walls that utilize advanced high-temperature composites to achieve flight-weight goals. Through a progressive test program utilizing the Durable Combustor Rig (DCR) at NASA Langley, the thermal-structural performance of actively-cooled combustor concepts will be matured. The initial focus will be on a hydrogen-cooled hybrid ceramic matrix composite (CMC) metal combustor panels scheduled for FY07 tests (HYP.2.01.33). Longer term, higher payoff research efforts will focus on developing actively-cooled, lightweight CMC combustor panels (HYP.2.01.34). Industry support will be established to develop fabrication methods for internal cooling channels and material improvements that increase conductivity and temperature capability to 3000 °F (HYP.1.01.65). In collaboration with the Hypersonic Propulsion Discipline Team, TBCC technology development efforts will focus on meeting performance requirements for lightweight γ -TiAl compressor and Ti-alloy fan blades. This will require establishing manufacturing and technology development collaborations with the AFRLs.

Integrated TPS and Hot-Structure Airframe Concepts.—This effort focuses on assessing airframe performance and thermal-structural analysis of key components of TSTO HRRLS type vehicles. Multi-mission, high-temperature leading edges, acreage TPS, control surface structures, as well as lightweight propellant tanks are enabling technologies for this and other classes of hypersonic vehicles. The goal will be the validation of design and analysis tools (HYP.2.01.C04), structural concepts and fabrication development for lightweight multi-mission airframe structures. As an initial effort, structural and analysis validation tests of an untested C/SiC Ruddervator control surface from the X-37 program (HYP.2.01.42) will be conducted. This test effort will acquire unique structural information, such as high-temperature structural dynamic response and multi-mission combined thermal-mechanical loading data that will baseline current NASA thermal-structural analysis capabilities (HYP.2.01.48). There is a need for lightweight multi-use tank systems for future hypersonic vehicles which utilize hydrocarbon or cryogenic fuels. However, current resources limit

the proposed activity to design trades for conformal versus non-conformal tanks that are either structurally integral (load sharing) or non-integral with the airframe (HYP.2.01.55).

In order to enhance and extend design knowledge for the hypersonic technical community, NASA analyses and testing of components will be offered to outside partners. If partnerships cannot be established, NASA will be limited to performing design and trade studies to guide future developments.

Integrated M&S Analysis and Design Methods.—A main thrust of the M&S level 2 effort is the development of structural design and analysis tools that provide reduced design cycle time and improved mission life assessment. This activity will consist of two parallel development efforts:

- Improved coupled thermal-structural analysis capabilities for hypersonic structures.
- Integrate thermal-structural analysis with level 1 durability/life prediction methods.

A baseline assessment of existing thermal and structural analysis methods for hot structures will be performed with respect to analysis cycle time and solution accuracy. This assessment will be performed using the X-37 C/SiC Ruddervator subcomponent test results (HYP.2.01.42), available X-43 flight data, and DCR combustor tests (HYP.2.01.33 and 34). Gaps in analysis capability and bottlenecks in analysis cycle time will be identified and methods will be developed to improve analysis cycle-time and accuracy. For example, improved thermal modeling techniques are needed to overcome inherent incompatibilities between thermal and structural analysis methods to enable coupled aerothermoelastic analysis of non-insulated hot-structure components.

Design data established at level 1 under the Durable Structural Elements (HYP.1.01.C36) and Material Durability, Life Prediction, and Damage Tolerance Prediction efforts (HYP.1.01.C29) will be incorporated to enhance analysis capability. Integrating durability, life prediction, and damage tolerance design models with thermal-structural analysis tools has several technical challenges that must be addressed. However, the benefits will be simultaneous assessment of material degradation impact to the entire structural performance of an airframe or propulsion component over its designed service life. Validation of the proposed integrated analysis and life prediction capability is critical. As a result, the M&S team will aggressively pursue opportunities to test propulsion, airframe, and tank structures through Government and industry partnerships.

Extreme Environment Structural Sensors.—Robust sensors are required to monitor and assess structural system health and provide valid measurements of performance for model validation. NASA facilities have the capability to test and qualify hypersonic structural concepts under relevant flight environments beyond our ability to make direct valid measurements to evaluate performance for both ground and flight-test structures. The lack of accurate data hinders the ability to validate and optimize component design which leads to increased margins and vehicle weight. Durable sensor technology needs includes strain measurements at 2000 °F and beyond, as well as accurate measurements at cryogenic temperatures, accurate in-situ heat flux measurements, high- and low-temperature pressure transducers and accelerometers, and accurate liquid level sensors for lightweight tank operations. The objective of this task is to identify and develop materials and structures sensor technology relevant to testing requirements for ground and flight applications. Sensor development efforts will be coordinated with the Hypersonic Experimental Capabilities team (HYP.1.04.C06) and other ARMD FA projects to eliminate resource duplication.

Further structural sensor technology improvements will include sensory materials, nano-sensors, and embedded sensors. The SBIR process will augment the development of sensor technology for TSTO HRRLS and HMMES applications. Promising technologies and attachment techniques will be integrated onto available hypersonic tests for evaluation and validation throughout the project.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.01.C01 2007 Q2	Define SOA Technology Baseline for Hypersonic Structures, Loadings, and Environments		Define SOA technology for propulsion, airframe and tank structures and relevant loadings and environment for hypersonic vehicles.	Way point--no metric available.	Document defined design requirements for M&S technology development.
HYP.2.01.C02 2010 Q4	Multi-Cycle Propulsion Structural Concepts	HYP.2.01.33 HYP.2.01.34	Development and validation of propulsion structural concepts (e.g., engine wall concepts, seals, etc). Include structural design/analysis and available material life prediction models for high payoff C/SiC and CVI SiC/SiC material systems.	Demonstrate combustor component durability in relevant scramjet environments through increasing temperatures up to 2800 °F and five thermal cycles.	Experimentally validated structural concepts for actively-cooled combustor walls. Documentation of design and test results.
HYP.2.01.33 2007 Q3	Test of Lightweight, Multi-Use, Actively-Cooled Metallic Combustor Concepts (DCR Experiment)	HYP.2.01.31 HYP.1.01.62	Validation of structural concept and analysis methods for an actively-cooled metallic panel. Anticipate both dynamic and static seals tests as part of this test.	Demonstrate 1600 °F durability of actively-cooled flight-weight metallic panel for five 5-minute cycles in a scramjet simulated environment	Actively-cooled metallic combustor panel concept. Documentation of design and test results.
HYP.2.01.34 2009 Q3	Test of Lightweight, Multi-Use, Actively-Cooled CMC Combustor Concepts	HYP.2.01.33 HYP.1.01.62 HYP.1.01.63 HYP.1.01.64 HYP.1.01.65	Design and fabricate a CVI SiC/SiC CMC structural concept for an actively-cooled combustor panel.	Demonstrate 2200 °F durability of actively-cooled flight-weight CVI SiC/SiC panel for five 5-minute cycles in a scramjet simulated environment	Actively-cooled CVI SiC/SiC combustor panel structural concept. Documentation of design and test results.
HYP.2.01.C03 2011 Q3	Integrated TPS and Hot-structure Airframe Concepts	HYP.2.01.42	Multi-mission performance of advanced hot-structure airframe concepts must be modeled and models must be validated with tests. Focus will be test opportunities for airframe leading edge, acreage, and control surface structures as available. <i>Developing test structures through Government and Industry partnership required.</i>	Demonstrate durability of CMC integrated airframe structures with 10% reduced weight as compared to defined SOA vehicle weight.	Experimentally validated structural concepts for lightweight hypersonic airframe components. Documentation of design and test results.
HYP.2.01.42 2007 Q4	Test of Hot-Structure Control Surface	HYP.2.01.31 HYP.2.01.48	Acquire multi-cycle thermal and structural data for a representative hypersonic structure (X-37 C/SiC Ruddervator). Data will be used to assess the state of thermal, structural, and modal analysis capabilities. Analysis gaps will be identified and subject of further structural analysis improvements.	Baseline test performance of control surface with analysis predictions to within 10% under simulated re-entry thermal and mechanical loading.	Test and analysis validation data of a hypersonic control surface subjected to acoustic, vibration, combined thermal/mechanical loads. Documented test procedures for hot ground-vibration testing. Documentation of ruddervator design and test results.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.01.C04 2011 Q4	Integrated Materials & Structures Analysis and Design Methods	HYP.2.01.48 HYP.2.01.50 HYP.2.01.51 HYP.2.01.55	Development of integrated design and analysis tools for structural concepts that incorporate material life prediction and reliability models. Design and analysis tools would be applicable to hypersonic airframe and propulsion structural systems. Tools incorporate thermal and mechanical structural response to environmental loads (i.e., thermal, pressure, vibration, and acoustic).	Validation of structural design, analysis, and failure mode prediction tools for hypersonic structures. Predictions to within 10% of measured parameters under simulated hypersonic environmental loads.	Coupled thermal-structural analysis methods for the design and analysis of propulsion and airframe structural concepts. Documentation of methodology/tools and validation test results.
HYP.2.01.C05 2011 Q4	Extreme Environment Structural Sensors	HYP.2.01.48 HYP.2.01.50 HYP.2.01.51 HYP.2.01.55	Develop and evaluate advanced sensor systems utilizing available structural and propulsion ground test programs. Validate sensor system required sensors for structural performance measurements.	Validate sensor technology to strain data at 2500 °F	Strain monitoring capability and documentation.

HYP.2.02—Propulsion

The primary technical challenges for the Propulsion Discipline are to significantly enhance the capability to design and predict the performance of hypersonic propulsion systems. Presently, this need is not adequately met by the state-of-the-art, as evidenced by the lack of hypersonic engines simultaneously capable of meeting weight, performance, operability, life-cycle, uncertainty constraints and cost requirements, as dictated by NASA and/or DoD mission scenarios. The propulsion technologies will be focused on combined cycle, airbreathing propulsions systems to enable HRRLS, refer to Figures 1 and 3. TBCC propulsion for hypersonic applications requires high Mach turbine engines to accelerate the vehicle to scramjet takeover speeds. Major challenges are to develop a turbine accelerator with Mach-4+ capabilities and develop a compatible scramjet to enable transition from low speed to high speed at $M < 4$. Similarly, RBCC propulsion requires optimization of the rocket and ram/scramjet cycles in a common flowpath. Integration of the high and low-speed propulsion systems into a combined cycle system as well as integration with the inlet/nozzle systems to the vehicle must be considered even at the level 2 discipline level. To this end, the proposed level 2 propulsion activity is comprised of five themes: 1) Scramjet/ramjet propulsion, inclusive of materials and structures, 2) High Mach turbine propulsion, 3) TBCC, 4) RBCC, and 5) Analysis and design tool development.

Our primary technical approach is to perform experiments to acquire data that will be used to develop and validate design and analysis tools. This will be done by leveraging existing NASA data and propulsion component and system hardware; as well as, using data and hardware obtained through collaboration with industry, academia, and other government entities. Additionally, level-2 design and analysis tool development tasks will be enhanced using the output from level-1 tasks. The proposed propulsion tests/experiments are linked with the guidance, navigation, and control (GN&C) and Experimental Capabilities Discipline tasks. Propulsion materials and structures work is coordinated with the Materials and Structures Discipline tasks. Propulsion analysis and design tool development tasks are also a joint effort with the Aero/Aerothermodynamic and Plasmadynamics Discipline team and leverage existing capabilities in FAP Subsonics and Supersonics. Work described herein is primarily at the propulsion component level and supports level-3 milestones HYP.3.01.29/36 and level-4 milestones

HYP.4.01.05/10/12/14/19 to develop predictive capability and technologies to enable HRRLS. The following presents a succinct description of the technology development efforts for each of the propulsion themes.

Scramjet/Ramjet Technology Development (HYP.2.02P01/06/33/55/48/49/10): The scramjet/ramjet element focuses on providing capability to: 1) reduce ramjet take-over flight Mach numbers, 2) transition from ramjet to scramjet, 3) predict performance from Mach 3.5-10, and 4) characterize hypervelocity (Mach>10) scramjet propulsion. A dual-mode transition experiment will be conducted at the LaRC AHSTF to address its operational characteristics including establishment and stabilization of the thermal throat, as well as fueling, and performance. Hypervelocity testing will be conducted at HyPULSE to address combustion physics at flight enthalpies exceeding Mach 10. Collectively, these databases will allow for the enhancement of the physical models required to address scramjet/ramjet propulsion.

Additionally, the Scramjet/Ramjet task is comprised of a Materials and Structures sub-element which addresses three level-2 milestones (HYP.2.02.48/49/10). The DCR, a modular, flight-like scramjet structure testing apparatus, will be tested at the NASA LaRC DCSTF to acquire a database for durability and life-cycle modeling. Gaseous hydrogen-cooled and ceramic-matrix panels are scheduled for testing. Both static and dynamic seals for high temperature and pressure environments and combustion acoustic structural loads will be characterized. Integrated wall/back structures and light weight actively-cooled structures will also be evaluated. This work is closely integrated with the Materials and Structures Discipline activity.

High Mach Turbine Technology Development (HYP.2.02.P02/01/02/11): The High Mach turbine engine element focuses on providing capability to bridge the gap from SOA Mach 2 to Mach 4-5 (unique to Hypersonics Project) which is required for transition to scramjet take-over. Based on the NGLT TBCC TSTO and NASP High Speed Propulsion Assessment (HiSPA) studies, a turbofan/ramjet variable cycle engine is best suited to satisfy the access-to-space mission requirements by maximizing thrust-to-weight ratio, while minimizing frontal area and maintaining high performance and operability over a wide operating range. The turbine core engine technologies will be leveraged from the Subsonics and Supersonics Projects (increased loading, reduced part count, etc); whereas, the Hypersonics Project will focus on the critical technologies unique to enable a Mach-4+ turbofan/ramjet engine. Specifically, to maintain performance and operability over a wide operating range inclusive of take-off, acceleration through transonic to scramjet takeover, and engine throttling to windmilling mode of operation; requires a unique high pressure ratio fan stage and hyperburner that can accommodate variations in bypass ratio (10X), fan rotor speed (7X), inlet mass flow (3.5X), inlet pressure (8X), and inlet temperature (3X).

Two major tasks are proposed: 1) Mach-4+ fan/compressor performance and operability studies and 2) hyperburner performance and flame stability studies. Task 1 will leverage an existing Mach-4+ fan stage rig to provide benchmark data characterizing the fan stage aerodynamic and aeromechanic performance and operability. Power-on and hypersonic unique “windmilling” databases will be generated. Inlet distortions defined by a large scale, TBCC inlet test will be used to study inlet/fan interactions. Pre- and post-test CFD simulations will be compared to the resulting experimental data to assess the capability of the SOA tools to predict performance and operability. Additionally, this effort will support model development in Propulsion level-1 (HYP.1.02.01/09) to predict fan and inlet stability limits and inlet/fan and compressor interactions. Task 2, similarly, will leverage an existing flame stability rig developed/delivered under NGLT to assess performance, mixing, flame holding, and fuel staging methods in an environment typical of a hyperburner in a Mach-4+ turbofan/ramjet engine. The National Combustor Code (NCC) and VULCAN will be used to model existing hyperburner/augmentor test data.

A potential follow-on phase, dependent on industry or OGA collaboration, would involve full scale hyperburner testing to address combustion scale effects as well engine interactions.

TBCC Performance Assessment (HYP.2.02.P02/03/07/11/43/51): The TBCC element addresses the integration, operability, and control of multi-flow path propulsion systems. Emphasis will be focused on addressing these issues for a dual inlet system typical of previous hypersonic over-under propulsion concepts. A small-scale screening program will be conducted in the 1- by 1-Ft Supersonic Wind Tunnel at NASA Glenn Research Center (GRC) to address mode transition, and to evolve the design. A subsequent large-scale demonstration will be performed to acquire data to address 3D inlet flow capture, pressure recovery, transition, and inlet-unstart. This testing includes two phases in the 10- by 10-Ft Supersonic Wind Tunnel at NASA GRC. The first phase will develop the variable geometry, boundary-layer bleed, and control systems required for stable operation from Mach 2 to 3.5. A potential second phase, dependent on collaboration with industrial or government partners, would include a small turbojet engine to demonstrate that the air induction system can stably transition from turbojet to ramjet modes. Data from these experiments will be used to validate modeling tools, assess scaling effects, quantify distortion characteristics and develop control strategies.

Additionally, the TBCC task is comprised of a Propulsion-Airframe Integration sub-element focusing on the development of analytic models for use in the design environment. Emphasis is placed on the capability to generate tip-to-tail solutions, inclusive of control-surface interactions with the nozzle flow field. This effort is highly dependent on DoD programs to acquire hypersonic flight data for validation purposes; however, existing NASA flight data (i.e., X43A) will be utilized. In addition, the physics of external burning for thrust augmentation will be examined.

RBCC Performance Assessment (HYP.2.02.P03/15/17): The RBCC element addresses issues related to air-augmented rocket design and performance. An existing direct-connect RBCC flow path rig will be tested at the NASA GRC Engine Components Research Laboratory (ECRL) 1B facility. This test will examine two distinct low-speed operational scenarios (Independent Ramjet Stream and Simultaneous Mixing and Combustion), transition to ramjet mode, and associated control strategies. “Ducted rocket” phenomena will be investigated numerically including the use of pulsed primary flow. These results will be used to validate and extend cycle modeling and reacting-flow analysis.

Analysis and Design Tool Development (HYP.2.02.22/40/04): The Analysis and Design Tool element addresses the development and validation of design and analysis methods. Numerous comprehensive studies have concluded that the SOA analysis methods do not adequately quantify the performance of hypersonic propulsion systems (Ref. Drummond et al). Three research topics to develop/enhance and validate design and analysis tools are proposed: 1) CFD tools concentrating on RANS modeling addressing combustion, LES, and other algorithms emphasizing turbulent combustion physics (steady and unsteady), 2) engineering level performance tools, analytic and/or CFD, inclusive of mixing and combustion physics models, and 3) multidisciplinary/multiblock-integrated tools including conjugate problems in aerodynamics, heat transfer, and mechanical loads. This effort will integrate the results of level 1 activities as they become available and involve collaboration among the NASA Fundamental Aero Programs, industry and universities.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.02.P1 1) 2007 2) 2010 3) 2010 4) 2011 5)2011	Scramjet/ Ramjet Technology Development		1) Assess and document consensus SOA (SOA) 2) Acquire benchmark ramjet/scramjet data to address ignition, flame-holding and turbulent flame propagation physics 3) Acquire ramjet-to-scramjet mode-transition and isolator data to characterize performance, control algorithms requirements, engine/vehicle performance requirements (e.g., pitch-control authority), and operability constraints. 4) Acquire benchmark hypervelocity combustor data. 5) Utilize data to develop enhanced models.	1) Documentation of consensus SOA. (2007,Q2) 2) Verified model predictive capability for ignition, flame-holding and combustion efficiency to within 10%. (2010) 3) Verify predictive capabilities against the goal of 10% accuracy on performance and operability. Demonstrate through test and/or simulation, control algorithms that maintain performance and operability to within 15% of predicted levels/margins. (2011) 4) Verify enhance modeling capability against the goal of predicting thrust to within 10%. (2011) 5) Obtain, document and disseminate benchmark data sets. (2011)	1) Document consensus SOA for airframe-integrated ramjet/scramjet test techniques, design/analysis tools/methods, and performance levels. 2) Benchmark data sets. Enhanced ignition, flameholding and turbulent flame propagation models. 3) Mode-transition and isolator data sets. Computed performance and operability limits. Established pitch-control requirements/design guidelines for mode-transition. Control strategies and candidate algorithms. 4) Benchmark data sets. Computed performance levels for hypervelocity combustor. Identify modeling shortcomings and recommended mitigation strategies. Enhanced modeling capability, verified against thrust prediction goals.
HYP.2.02.P2 1) 2007 2) 20072009 3) 2008, 2010 4) 2011	High-Mach Turbine Technology Development	HYP.1.01.C01 HYP.1.04.C02 HYP.1.02.C01 HYP.1.02.C02 HYP.1.02.C04 HYP.1.01.C01 HYP.1.01.C03 HYP.1.01.C04 HYP.1.02.01 HYP.1.02.02 HYP.1.02.03 HYP.1.02.04 HYP.1.02.05 HYP.1.02.06	1) Asses and document consensus SOA. 2) Acquire benchmark aerodynamic and aeromechanic performance and operability data from an existing Mach 4 turbine engine design (RTA) fan-stage rig. 3) Utilize an existing Mach 4 augmentor/ramburner flame stability rig to acquire performance and operability data and compare to the predictions. 4) Complete a full 3-D Navier Stokes simulations of the entire fan stage and multistage core compressor for a Mach 4 turbine based combined cycle engine including the multiple bypass ducts.	1)Document consensus SOA (2007). 2) Quantify uncertainty in SOA fan performance and stability models. Validated CFD codes provided prediction is within 5% of stall margin and 0.25% of efficiency over the entire operating range. Fan aerodynamic operability range increased by a factor of 3. (2007, 2009) 3) Quantify uncertainty in SOA combustor/hyperburner performance and mixing models. Hyperburner operability range increased by a factor of 10 as measured by swings in bypass ratio to maintain flame stability and acceptable performance. (2008, 2010) 4) Validate Variable cycle operation over a 10X swing in bypass ratio and a 6X swing in fan rpm. Multiblock version validated provided Fan performance predicted within 5% stall margin and 0.25% in efficiency of the data in HYP.2.02.01. (2011)	1) Document consensus SOA for Mach 4 TBCC engine component test techniques, design/analysis tools/methods, and flowpath performance and operability levels - specific to a Mach - fan stage and augmentor/ramburner subject to a 10X variation in bypass ratio. 2) Document high-Mach Fan Stage: Benchmark Aerodynamic and aeromechanic database including windmill operation. 3) Document assessment/ calibration of SOA design and analysis tools for Key components of Mach>4 Turbine Engine: Fan Stage & Hyperburner. 4) Document hyperburner Database: Flame Stability Limits Defined and Performance data over a 10x change in bypass ratio.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.02.P3 2011 With annual assessments	Turbine Based Combined Cycle Performance Assessment	HYP.1.02.49	Assess and document consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for TBCC inlets. Develop candidate TBCC propulsion system architectures and operational sequences for mode transition. Identify fundamental issues/challenges. Conduct validation testing for inlet operability, control, and performance during mode transition. Develop tools to predict performance, weight, and durability of TBCC propulsion systems.	Document consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for TBCC inlets. Transition from turbo to ramjet modes demonstrated at large scale. Performance prediction for integrated propulsion system to within 10%. Weight prediction to within 10%, and durability of critical components to within TBD.	Documentation of consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for TBCC inlets. Small-scale screening tests complete and results archived (2007), reference structural architecture defined (2008), large-scale tests completed and results documented (2011), TBCC performance and weight models delivered (2011).
HYP.2.02.P4 2008 2009 2010 2011	Rocket Based Combined Cycle Performance Assessment		Assess and document consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for RBCC systems. Develop candidate RBCC system architectures, operational sequences, and control schemes for mode transition. Use existing hardware to validate various low speed cycles and transition to ramjet mode. Alternate vacuum-mode cycle options will be explored numerically. Design tools for inlet integration will be developed in order to enable optimized 3-D configurations. Develop tools to predict performance, weight, and durability of RBCC systems.	Document consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for RBCC propulsion systems. Transition from various low-speed to ramjet modes demonstrated experimentally. Preferred cycle options for various applications determined. Performance prediction for integrated propulsion system to within 10%. Weight prediction to within 10%. Ability to perform 3-D inlet integration screening calculation in 30-minutes.	Documentation of consensus SOA test techniques, design/analysis tools/methods, and flowpath performance and operability levels for RBCC propulsion systems (2008). Reference structural architecture (2009), low speed cycle experiments complete and results documented (2011), analysis of alternate vacuum-mode cycles complete and results documented (2009), 3-D inlet integration screening tool (2010), Performance and weight prediction tools (2011).

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.02.P5 2007 2011	Analysis and Design Tool Development		1) Assess consensus SOA analysis 2) Enhance CFD algorithms in the areas of: a) RANS, b) LES and c) unsteady (time-dependent) analysis methods. 3) Enhance the capability of engineering-level cycle performance tools. Construct algorithms for incorporation into system level trade tools. 4) Address multi-disciplinary tools capable of analyzing aero/structural heat transfer problems, and aero/mechanical turbomachinery problems.	1) Validate advanced/enhanced turbulent combustion algorithm predictive capability to assess static-pressure distribution to within 10%, and global heat transfer rates to within 15%. 2) Verify enhanced modelling capability to assess (isolator physics) normal-shock-train pressure recovery and associated length scales to within 10%, and validate dual-mode propulsive engine/combustor performance predictions (versus experimental data) to within 10%. 3) Unify tools in aero/structural and aero/mechanical disciplines to a single algorithm, without degrading either codes net-execution time (to run an individual problem).	1) Document consensus SOA (2007) 2) Document results and archive in an electronic format (2011). 3) Document enhanced algorithms and archive in an electronic format (2011). 4) Document algorithms/codes and archive in an electronic format (2011).

HYP.2.03—Aerodynamics, Aerothermodynamics, and Plasmadynamics

At level two, we combine the tools developed under level 1 into a more comprehensive toolset to capture the interactions of multiple physical effects. These effects include: radiative heat transfer, transition and turbulence, chemical reactions, nonequilibrium thermodynamics, and gas-surface interactions. These phenomena require the solution of additional equations or evaluation of model expressions to include their quantitative impacts on the flowfield and bodies.

Radiative heat transfer becomes significant relative to convective heat transfer when the size and temperature of the radiating regions become large. This is particularly important for entry systems, columns 1 and 2 of Figure 1 including some concepts being considered for the HMMES mission. Its inclusion in simulations requires solution of the radiative transfer equation coupled with the flow solution; modeling is required because the computational cost of a full solution is too high. Quantities dependent on the frequency variable cannot be fully resolved, but their average effects can be included through various mathematical approximations. Opacity binning and macroscopic models will be implemented and compared to assess their effectiveness in hypersonic simulation. Similarly, angular dependence of the radiation is also expensive to treat directly but can be handled through various modeling approaches. Characteristic-based methods and macroscopic models will be implemented and compared to achieve the desired accuracy at acceptable computational cost. This effort will be done under milestone HYP.2.03.07 and will be incorporated into the advanced flow solvers developed under level 1.

Turbulence has a profound effect on convective heat transfer in hypersonic flow, on surface effects such as ablation, on drag, and on radiative effects such as afterbody heating. The spatial extent of the turbulent region depends in turn on the location of the transition region; thus, predictions of this location and the downstream evolution of the turbulent flow are crucial to accurate simulation. Such predictions require turbulence models valid at hypersonic speeds and numerical methods that can supply highly resolved flow solutions as inputs to the models. While some features of turbulence can be handled with relatively simple, RANS models, these models require careful ad hoc parameter tuning and input of

transition locations; this is particularly difficult for complex body shapes. Much more general turbulence modeling, at increased cost, is provided by LES methods and hybrid (RANS/LES) methods. LES does require well-resolved flow solutions which will be attained by the high-order methods being developed under level 1, for example under HYP.1.03.11. SOA LES methods, developed largely for low-speed flows, must be extended to include real-gas and surface-interaction effects to be valid for hypersonic flow. This effort is particularly important to ascent (HRRLS) and cruise vehicles.

In HYP.2.03.03, the level 1 effort of HYP.1.03.48 is extended to develop simulation tools that can provide solutions to within user specified errors including uncertainty bounds of physics models. This effort, if successful, can have very significant payoffs by reducing the total computer time required through the compound effect of reducing the number of mesh points with automated solution adaptivity and reducing the number of iterations by automatically satisfying user specified error bounds. The technique should be applicable to all vehicle classes.

Milestone HYP.2.03.14 extends the work of HYP.1.03.21 to an integrated tool that models gas-surface ablation interaction including the effects of weakly ionized reacting flows. This work will be important for entry systems such as HMMES and CEV. These more advanced models will be incorporated into the high-fidelity codes developed in level 1.

Under milestone HYP.2.03.15, we evaluate and compare pre-flight data and pre-flight uncertainty to flight data for multi-stage and air-breathing configurations such as Hyper-X, which have applicability to the HRRLS mission. Advanced CFD tools developed at level 1 will be used to evaluate test uncertainties including support interference. Experimental test techniques will be develop for coupled internal and external flows at subscale with flow through inlets on hypersonic vehicles and for the study of uncertainties in interference aerodynamics of stage separation of co-linear and parallel bodies.

Aeroelastic-induced instabilities experienced by vehicles in the hypersonic flow regime include aerothermoelastic deformations and panel flutter. In addition, understanding and modeling fluid-structural interactions are important for design of inflatable decelerators such as ballutes which may enable the HMMES mission. In milestone HYP.2.03.02 new methods based on staggered integration that will time accurately couple aerothermal loads with structures will be developed. This work is particularly important for planetary entry systems.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.03.02 2011 Q3	Aeroelastic Assessment	HYP.1.03.C02	Lightweight structures flex under aerodynamic loads. High temperatures associated with high heating rates result in additional complexities associated with varying thermal expansion and temperature dependent structural coefficients. Establish sub-scale aerothermoelastic ground test techniques to verify analysis tools with these complexities.	FY07: Obtain initial hypersonic aeroelastic test data of a 4 in. flexible ballute model. Compare with aeroelastic predictions, prediction and test technique validated if within 5% of measured max deflection. FY08: Obtain hypersonic aeroelastic test data for a flexible engine inlet Compare with aeroelastic predictions, prediction and test technique validated if within 5 % of measured deformation.	Documented test technique for hypersonic aeroelastic datasets on flexible configurations.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.03.03 2011 Q2	Hypersonic Flowfield Simulations to User Specified Error and Uncertainty Bounds Using Automated Solution Adaptivity	HYP.2.03.11 HYP.1.03.15 HYP.1.03.23 HYP.1.03.27 HYP.1.03.30 HYP.1.03.48	Extends goal of HYP.2.03.11 by including uncertainty of physics models that are independent of grid quality within the numerical simulation.	FY09: Demonstrate factor of 100 reduction in total computer time with automated solution adaptivity (including error bounds and uncertainty bounds) for steady realistic 3D configuration. FY11: Demonstrate time-dependent adjoint approach for model problem & assess extension to realistic 3D configuration to enable factor of 100 gain for time-dependent flows with NRA support. SOA baseline defined by HYP.1.03.63.	CFD code capable of obtaining solutions to within user specified bounds.
HYP.2.03.07 2011 Q4	Coupled Heat Radiation-Flow Simulations Capability	HYP.1.03.11 HYP.1.03.07 HYP.1.03.20	Advanced simulation capability based on combined flow and radiation solution algorithms, research to include axisymmetric simulations coupling the radiative heat transfer to the flow field solution and also first-principles quantum chemistry, and fluid-surface interaction methods.	FY10: Electron-impact excitation cross-sections and chemical reaction rates improved in reliability relative to current values by 50%. FY11: Thermodynamic properties of carbonaceous species CN, C2, CO, C3, C2H, CO2, and CH2 improved in reliability by 50% relative to current values. Ablation properties of Teflon improved by 25% over current models. SOA baseline defined by HYP.1.03.63.	CFD code with coupled radiation, quantum-chemistry based models, and non-equilibrium flow interactions.
HYP.2.03.08 2011 Q4	Hypersonic Flow LES	HYP.1.03.C03 HYP.1.03.C05 HYP.1.03.C01 HYP.1.03.C02 HYP.1.03.C08 HYP.1.03.C10, HYP.1.03.C07 HYP.1.03.C12 HYP.1.03.C14 HYP.1.03.C15	LES provides best, near term promise for understanding complexities of separated turbulent flows and impact on things like base heating and thermal protection system requirements.	FY10: Perform LES with high order method to evaluate effect of different sub-grid scale models for a hypersonic flow with shock bl interaction. FY11: Develop sub-grid modeling methodology adapted to requirements of hypersonic flow. Models validated against experimental data, for attached & separated hypersonic turbulent flows. Accuracy of LES models improved 25% over baseline. SOA baseline defined by HYP.1.03.63 and HYP.1.03.C01.	CFD code for LES simulation for attached and separated flows.
HYP.2.03.14 2011 Q4	Non-equilibrium Hypersonic CFD Tools With Surface Interactions Capability	HYP.1.03.09 HYP.2.03.10 HYP.2.03.04 HYP.1.03.C05 HYP.1.03.C07 HYP.1.02.C05 HYP.1.02.C06 HYP.1.03.21	Integrate tools that model gas/surface ablation interactions and weakly ionized reacting flows with SOA hypersonic CFD tools.	FY09: Determination of ablating surface chemistry mechanisms. Comparison of nitridation, oxidation, and heterogeneous recombination rate expressions with expressions used in current gas-surface interaction models. FY11: Improved rate data for Cu, Pt, SiC, silica, graphite, and carbon phenolic. Integration of gas/surface interaction modeling tools into CFD code. Compare improved modeling result with Arc Jet side arm and Arc Jet measurements. Validated if model rate is within 5% of measurements. SOA baseline defined by HYP.1.03.63 and HYP.1.03.C01.	CFD tools for non-equilibrium flows with surface interactions.
HYP.2.03.15 2011 Q4	Uncertainty Reduction in Hypersonic Aero Prediction and Database Development		Improvements in pre-flight predicted aerodynamics from experiment, CFD, engineering methods, and ground-to-flight scaling to yield flight databases with decreased uncertainties for complex hypersonic vehicles, including multi-stage and airbreathing configurations.	FY07-11: Reduce hypersonic pre-flight aero prediction uncertainty by 30% for complex hypersonic vehicles including multi-stage & air-breathing configurations. FY08: Design & fabricate "as flown" Hyper-X model to evaluate contribution of modeling to uncertainty budget. FY09: Design & fabricate "as flown" Hyper-X configuration which integrates flow-through test technique development results to include cowl-open flow-through effects at sub-scale. FY10: Interference aerodynamics uncertainty reduction for hypersonic stage separation of co-linear bodies (e.g., Hyper-X). FY11: Interference aerodynamics uncertainty reduction for hypersonic stage separation of parallel bodies (e.g., belly-to-belly, back-to-back). SOA baseline defined by HYP.1.03.63 and HYP.1.03.C01.	Experimental aerodynamic database for hypersonic configurations.

HYP.2.04—Advanced Control Methods

Hypersonic vehicles pose unique challenges to GN&C. The objectives of the GN&C program are to a) develop next-generation guidance and control algorithms that address these challenges, with particular applicability to multi-mission/multi-propulsion element/multiple-Mach regimes, and b) develop the accompanying ground simulators and flight experiment test-beds. The development will occur along three general application areas which apply to the HRRLS and HMMES mission classes: Capsule/Re-entry Probes, Hypersonic Gliders, and Powered Gliders (see Table 1).

The Capsule/Re-entry Probe (HMMES) will include application to advanced blunt shapes (manned/unmanned re-supply) as well as planetary probes. The problem regarding landing heavy payloads on the surface of Mars will be a focus. Advanced GN&C techniques will improve landing accuracy, maintaining the vehicle trajectory along prescribed constraints (e.g., minimize deceleration loads, aeroelastic coupling of decelerators) as well as enable precision Mars missions while minimizing expenditure of propellant during final descent. Advanced probe designs (e.g., SCRAMP, deployable or ballute designs) permit unique drag-modulation and reduce EDL sub-system mass for accurate placement of payloads/instruments/rovers.

For Hypersonic Gliders (HRRLS Re-entry), advanced GN&C will lead to improved trajectory design and landing accuracy given such effects as changing outer mold line (OML) (e.g., ablation effects on Falcon Hypersonic Technology Vehicle (HTV) series), control of system dynamic effects such as roll, spiral, Dutch-roll modes. Of importance is the development of adaptive control which can permit controlled flight without a detailed aerodynamic model (e.g., of use across Mach regimes), with excursions away from the model (e.g., unplanned departures from aerodynamic geometry; accidents) or for flight with an uncertain atmospheric model (planetary entry). For waverider concepts, control during exo-atmospheric skips, or of viscous interaction effects across a large Mach number span is of significance.

Finally, Powered Gliders (HRRLS) involve the combined effects of the “glider” with a powerplant (e.g., rocket, scramjet, RBCC, TBCC). These systems are typically poorly modeled powered vehicles that have strong system-wide coupling between propulsion and aerodynamics, and have thin performance margins necessitating operation near system constraints to achieve efficiency. This level of integrated functionality may represent a major advance. Current generation linear control systems are not viewed as sufficient for the efficient resolution of control, plant, and complex fluid interactions. In these applications hierarchical control structures interacting with simpler sub-system controllers are viewed as particularly attractive.

Table 1. Hypersonic vehicle design regimes, relevance and application.

Hypersonic Flight Article	L/D	Applications	GN&C Attribute	GN&C Relevance	GN&C Challenge
I. Capsule/ Adv. Probes (HMMES)	L/D<1	Landing large Mars payloads, CEV, Advanced Planetary probes, Aeroassist	Roll modulated, Drag modulated (SCRAMP; Ballute class), 1-d adaptive control	Improved cross-range/crew safety; landing large payloads, precision targeting for planetary missions (<10 km; advanced <1 km)	Complex flows/coupling ($V>9\text{km/s}$); SCRAMP slots; Re-number dependency; challenging control surface/effector issues; aeroelastic effects
II. Hypersonic Gliders (HRRLS re-entry)	L/D>1	HTV 1,2,3; SOAREX Waverider Test-bed; TSTO; Aero-gravity assist, re-entry gliders	Multi-effector/high control authority, adaptive control	Improved control, trajectory optimization, targeting	Multi-surface, complex flow over Mach, OML change, sparse aero database
III. Powered Gliders (HRRLS)	L/D>1	X-43A; X51, ARES-SD, Scramjet Cruise Vehicle, RBCC, TBCC, TSTO	Multi-effector/engine cycle; prop. sys coupling effects; multiple control loops, adaptive, hierarchical control	Improved control; optimal coordination between control loops over Mach	As in II; strong engine/vehicle coupling effects, complex control interactions over Mach

The following proposed milestones will have approximately equal investment over four fundamental GN&C areas. Partnerships will be sought and SBIR and NRA calls will be used to enhance these efforts.

High/Low Fidelity Dynamic Model Tasks (HYP.2.04.100).—Develop HMMES and HRRLS mission relevant models incorporating the essential coupled dynamic system elements. These include airframe, propulsion system, sensors and effectors, etc. and their interactions. Low-fidelity (control design) models will support advanced control methods and architectures research (2007-2011). High-fidelity (physics-based) dynamic models will be used for investigating control issues and for in-depth control validation (2008-2012). Validation will be done against simulation and flight data such as X-51A when it becomes available. Expected benefit will include reduced system design cycle time, increased mission reliability (>20%), and perturbation behavior from effects such as mode transition (>20%).

GN&C Advanced Algorithm Development Tasks (HYP.2.04.200).—Develop algorithms for trajectory shaping and control of future hypersonic vehicles, as well as hierarchical GN&C system architecture. This architecture, and its algorithms will address the challenges of modeling misspecification and uncertainty, and strong system-wide couplings. One area of effort will involve populating a hierarchical controller architecture with propulsion and aero subsystem controllers (the former involving ground experiment validation with the Propulsion Team), and testing with uncertainties and coupling effects (Gen 1 by 2008, Gen 2 by 2012). Other efforts will include adaptive control, general predictive control (GPC) and trajectory shaping logic, leading to simulation and flight experiments (e.g. Sub-Orbital Aerodynamic Re-entry Experiments (SOAREX), FRESH-Fx, Affordable Responsive Spacelift-Subscale Demonstrator (ARES-SD), and/or X-51). While some of the algorithm development is generic in nature, it would be applied to specific problems within HMMES and HRRLS missions. Expected benefit would include improved mission reliability of at least 20% for these mission types.

High Fidelity Simulator Tasks (HYP.2.04.300).—Develop by 2009 improved ground simulation capability, with emphasis on simulating performance under various types of uncertainty, system-wide coupling, and associated model uncertainty. These will be used as test-beds for testing and developing complex algorithms (e.g., adaptive, probabilistic, GPC, etc.) as well as interaction between different control systems (e.g., hierarchical, method of probability collectives, etc.). The X-43A simulator will be further utilized and evolved as the baseline with which to determine performance metrics enabling comparison between different GN&C paradigms. At least 20% improvement in specific parameter

Figure of Merit (FOM) (e.g., reliability, trajectory shaping, targeting; application specific performance identifier) for specific HMMES and HRRLS missions would be demonstrated by use of the newly developed simulation capability.

Advanced GN&C Hardware and Flight Experiment Tasks (HYP.2.04.400).—It is expected that the cost to perform focused GN&C flight experiments can be reduced by 5x using both available sounding rocket hardware, through partnership with other organizations (e.g., SMD, DoD), and by the selective use of multiple experiment ejection designs on the same flight opportunity. The continued SOAREX flight series will include hypersonic glider flights (HRRLS-class) in 2008 and 2011 to test/validate adaptive control techniques across the Mach flight regimes (full envelope GN&C). A Planetary Probe (HMMES-class) drag or roll modulation GN&C experiment will be conducted from the same vehicle. Using the proposed advanced control techniques, the expected >20% improvement in specific GN&C metrics (trajectory mid-point shaping, stability, targeting) can be attained. In addition, specific h/w tasks related to X-43A/X-51/Phoenix will achieve the >20% improvement GN&C variables related to complex system-wide and in particular propulsion/vehicle interactions. Flight and other hardware data will then be compared to ground simulator tasks for further evaluation and improvement.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.04.100 2011 Q4	High/Low Fidelity Models for Full Envelope GN&C	HYP.2.04.200 HYP.2.04.300 HYP.2.04.400	System dynamics models will be developed incorporating the essential coupled dynamic elements including: aero, propulsion, sensors, actuation systems, nav system degradation, CG and CP movement, aeroservoelastics, etc, and their interactions. High-fidelity (physics-based) dynamic models will be used for investigating control issues and for in-depth control validation. Low-fidelity (control design) models will support advanced control methods and architectures research.	Models used to develop control schemes that allow reduced system design overhead by 50%, increase mission reliability by 20%, and reduce undesirable transient behavior during mode transition by 20%. X-43A considered SOA baseline for these metrics	First generation low and high fidelity models developed, evaluated, and documented for hypersonic gliders by 2009. Second generation low and high fidelity models developed, evaluated, and documented for advanced planetary probe and powered glider (X-51 or ARES-SD) by 2011.
HYP.2.04.200 2011 Q4	Advanced Algorithm Development for Full Envelope GN&C	HYP.2.04.100 HYP.2.04.300 HYP.2.04.400	Hierarchical GN&C system architecture and its algorithms to address challenges of modeling misspecification and uncertainty and strong system-wide couplings. One effort involves populating a hierarchical controller architecture with propulsion and aero subsystem controllers, and testing with uncertainties and coupling. Other efforts include adaptive control and trajectory shaping logic.	Reduce system preliminary design overhead by 50% through reducing number of optimization/analysis cycles. Increase mission reliability for HMMES-class system by at least 20% over current GNC technology, as measured by Monte Carlo experiments. Reduce undesirable transient behavior during mode transition in a HRRLS system by at least 20%. Capture 90% EDL accuracy as measured by Monte Carlo experiments (to 10km and 1km target). X-43A considered SOA baseline for HRRLS metrics, MER considered HMMES baseline	First generation design tools and algorithms developed, evaluated and documented for hypersonic gliders by 2010. Second generation design tools and algorithms developed, evaluated, and documented for advanced planetary probe and powered glider (X-51 or ARES-SD) by 2011.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.04.300 2011	High Fidelity Simulator	HYP.2.04.100 HYP.2.04.200 HYP.2.04.400	Improved ground simulator with emphasis on simulating performance under various types of uncertainty, system-wide coupling, and associated model mis-specification. These will be used as test-beds for understanding complex algorithms (e.g., adaptive, probabilistic, GPC, etc.) as well as interaction between different control systems (e.g., hierarchical, probability collectives, etc.).	Simulator available incorporating advanced models and control methods for ref. vehicles and test flight opportunities (X43 baseline). Reduce undesirable transient behavior during mode transition and other common perturbation in a HRRLS system by at least 20%. Develop improved simulator which increases model integration by at least 50%. Develop improved Monte-Carlo turn-around time by at least 50%. Demonstrate through simulator at least 20% parameter (application specific; examples such as reliability, safety, trajectory shaping) improvement for advanced GNC control techniques for HMMES and HRRLS. X-43A considered SOA baseline for HRRLS metrics, MER considered HMMES baseline	First generation simulator developed, evaluated, and documented for hypersonic gliders by 2009 Second generation simulator developed, evaluated, and documented for advanced planetary probe and powered glider (X-51 or ARES-SD) by 2011.
HYP.2.04.400 2011 Q4	GN&C Flight Experiments	HYP.2.04.100 HYP.2.04.200 HYP.2.04.300	Baseline complex system-wide and propulsion/vehicle interactions with X-43A flight data. Evaluate initial X-51 in 2010. Evaluate SOAREX hypersonic glider flights in 2008 and 2010 to test/validate adaptive control techniques across the Mach flight regimes. Evaluate drag-modulation probe experiment, 2010, include such effects as aeroelastic, moving/OML changes. Flight data will then be compared to ground simulator tasks for further evaluation.	Full envelope GN&C flight test of one or more advanced control algorithms. Develop capability of performing focused GNC flight experiments by factor of at least 5x reduction in cost. Demonstrate through FLIGHT (SOAREX) at least 20% parameter (application specific; examples such as reliability, safety, trajectory shaping) improvement for advanced GNC control techniques for HMMES and HRRLES. X-43A considered SOA baseline for HRRLS metrics, MER considered HMMES baseline	Execute flight test, acquire data, and generate reports for 2008/2010 hypersonic glider tests, 2010 advanced planetary probe test, and 2010 X-51 test.

HYP.2.05—Experimental Capabilities

Experimental capabilities, in general, support the other hypersonic discipline teams by providing the tools and techniques needed to develop and validate hypersonic technologies. Within this topic, advanced instrumentation and diagnostic techniques will be integrated into facilities and test articles for use in relevant hypersonic environments. Implementing techniques developed in level 1 into facilities ultimately will provide higher fidelity and more detailed data to enhance the accuracy of research results. A focused investment to improve ground-test hypersonic facilities and flight-test platforms will be made to expand capabilities and increase quantification of facility flow attributes in support of specific requirements. These requirements include requests from researchers in the other discipline teams within hypersonics in addition to recommendations from recent studies that indicated that such measurement systems and facility upgrades should be implemented.

Pointwise Temperature and/or Velocity Measurement in Hypersonic Test Facility, e.g., AHSTF, 8-Foot High-Temperature Tunnel (8-Ft HTT) (HYP.2.05.31).— For ground testing hypersonic vehicles, it is very important to quantify the test conditions produced by the facilities so that correct inferences can be drawn from test results. Parameters of interest to high-speed engine modelers are freestream temperature, velocity, density, composition and RMS fluctuations of these parameters. Also, spatial distributions of these parameters should be measured to determine facility performance. Coherent anti-Stokes Raman spectroscopy (CARS) and Rayleigh scattering are two measurement techniques that

can be combined to provide these parameters at a single point in a flow. Such single-point measurements are preferable to line-of-sight measurements such as those made with diode lasers because spatially precise samples can be obtained on the flow instead of averaging through the boundary layers developing on the facility walls. CARS and Rayleigh scattering are thus being developed to be applied to some of the larger test facilities such as the Arc-Heated Scramjet Test Facility (AHSTF) and the 8-Ft High Temperature Tunnel (8-Ft HTT). The development of the CARS/Rayleigh system has been co-supported between 2004-2008 by NASA and the OSD, Defense Test Resource Management Center's (DTRMC) Test and Evaluation/ Science and Technology (T&E/S&T) program. The CARS/Rayleigh system is currently being applied to laboratories and smaller test facilities but the system will be improved and hardened for use in the larger facilities like 8-Ft HTT in this task.

Mass Flux Sensor (HYP.2.05.41).— The development and optimal operation of hypersonic inlets/propulsion systems requires an accurate measure of the inlet mass capture. The ability to non-obtrusively measure inlet mass capture will be a valuable diagnostics for both ground testing and possible integration into a flight sensor. Knowledge of the inlet mass flux is fed into the inlet/combustor control system to optimize the propulsion system operation.

Some demonstration tests of oxygen based TDLAS mass flux measurements for subsonic conditions have been performed under previous SBIR and NASA contract activities. In this effort, techniques for the measurement of inlet mass capture based on Tunable Diode Laser Absorption Spectroscopy (TDLAS) will be investigated/developed for non-intrusive measurements of the inlet mass flux. Three phases are planned: 1) Demonstration of an oxygen based TDLAS sensor system to obtain integrated path velocity and density measurements on a supersonic flow field with state properties similar to those anticipated in an actual inlet, 2) Development of a fiberoptically coupled transmitter/receiver in order to minimize space requirements, improve durability, enable locating the processing electronics in a remote location, and miniaturize signal processing electronics, and 3) Integration of the fiber optic mass flux sensor system into a GRC designed hypersonic inlet for testing in GRC's 1- by 1-Ft Wind Tunnel. Also, mass flux measurements will be taken over a range of inlet conditions in order to provide benchmark data for comparison against traditional mass flux estimates and for CFD code comparison.

This work may be leveraged by an NRA activity.

Evaluation of Sensors (HYP.2.05.03) and Facility Enhancements (HYP.1.04.34).— An important element of hypersonic technology development is experimental validation in ground test facilities. Some specific areas of interest include the effects of scale, test gas composition and conditions, and test time. There are several premier NASA facilities currently used supporting hypersonic testing which will require some corrections/ extrapolations to the simulated flight conditions. Of particular concern the majority of propulsion testing is conducted in test medium which include some form of vitiation. A combustion heated facility (i.e., 8-Ft HTT, CHSTF, GASL test legs, etc) utilizes a test gas which include the products of combustion, while arc heated facilities have elevated levels of nitrogen oxides, and storage heaters (i.e., pebble beds, etc) contain particulates. Improved instrumentation (measurement probes, gas sampling systems, calorimeter designs, etc.) must be developed to accurately quantify test flow conditions and composition to support fundamental experiments conducted by other discipline teams such as the evaluation of the effects of vitiation on flameholding and engine performance in scramjet engine testing. There is a need to expand, enhance, or provide capabilities in support of these upcoming activities, as well as integrate/ update advanced instrumentation/ measurement techniques into the facilities to optimize testing and maximize data accuracy.

PLIF Characterization of Arc-Heated Scramjet Test Facility (AHSTF) Freestream

(HYP.2.05.56).— The PLIF Technique provides an imaging capability for visualizing and performing quantitative measurements in hypersonic flows. The current embodiment of the NO PLIF technique at NASA provides flow visualization and relative velocity measurements. As part of a FY06 task, the velocity measurements will be extended to be absolute velocity measurements. In milestone HYP.1.04.38 the capability for temperature measurement will be implemented at NASA. The culmination of these improvements will be the characterization of the AHSTF which naturally produces 2-5% NO. NO PLIF will be able to determine the spatial variations in temperature, velocity and will visualize any irregularities present in the flow. These measurements will help engine modelers determine the inlet boundary conditions, including the turbulence intensity which is an input to their calculations. Such data will significantly improve the confidence and reduce the error bars in performance evaluation, while possibly explaining anomalies obtained during testing. If temperature measurement are required in turbulent parts of the flowfield such as inside the combustor or in the engine exhaust then this task will depend on successful completion of HYP.1.04.37, because two excitation/detection system are required for measuring temperature in turbulent flows with NO PLIF. In laminar flows, or those with modest fluctuations such as freestream flows, a single excitation/detection system suffices.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.2.05.57 2007 Q2	Level 2 SOA baseline consensus to evaluate metrics against		Document the SOA hypersonic experimental capabilities at level 2. Identify baselines to measure progress against for measurement techniques, and test environments.	Way point--no metric available	Technical Memorandum and/or journal article reporting level 2 SOA
HYP.2.05.31 2010 Q1	Pointwise Temperature and/or Velocity measurement in Hypersonic test facility, e.g., AHSTF, 8 Ft HTT	HYP.1.04.39	CARS/Rayleigh will be evaluated for use in 8 Ft HTT and other facilities	Measurement uncertainties of 5% of measured static temperature, velocity, and density or better.	Measurement system and Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.2.05.56 2010 Q3	PLIF characterization of AHSTF freestream	HYP.1.04.37	NO PLIF imaging used for measuring velocity and average temperature in AHSTF	Velocity measurement accuracy of 50 m/s; average temperature measurement accuracy of 7% (currently neither is directly measured)	Measurement system and Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.2.05.03 2010 Q3	Incorporate advanced measurement techniques into inlet/shock train/isolator test environment	HYP.1.04.34 HYP.1.04.63	Complete design and facility upgrades for focused experiments which will enable calibration/refinement of computational tools	Obtain flow field details (pressure, shock location, velocity) which will enable calibration/refinement of computational tools and ultimately provide a reduction of at least 50% on the error band for resultant performance evaluation (i.e., combustion efficiency, thrust, operational limits)	Measurement system and Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results
HYP.2.05.41 2011 Q3	Demonstration of optical inlet mass capture	HYP.1.04.19	Modify sensor system for demonstration in hypersonic inlet test	Provide time accurate nonintrusive inlet mass flux measurement. $\pm 10\%$ accurate total mass flow in tunnel environment	Measurement system and Report (Technical Memorandum, journal article, etc.) detailing experimental protocol and results

HYP.3.0

The primary objective of the Hypersonic Level 3 activities are to integrate the technology development efforts from the Level 2 discipline teams to develop multidisciplinary, highly-integrated design, modeling, and predictive capabilities (inclusive of their validation), for Hypersonic propulsion and/or

vehicle systems. To this end, the Level 3 efforts will be discussed with respect to Propulsion Systems Design, Vehicle Systems Design, and Experimental Capabilities. Propulsion system design activities are focused on combined cycle, airbreathing propulsion systems to enable Highly Reliable Reusable Launch Systems (HRRLS) - refer to Figures 1,2, and 3. Vehicle Systems Design efforts are focused on integrated structures which meet the environment for both HRRLS and HMMES missions. Experimental Capabilities leverage Government, industry, and academic facilities and measurement capabilities, augmenting where practical, to provide capability to validate Propulsion System Design and Vehicle System Design tools. Additionally, technology gaps in the Level-3 design and analysis tools and validation capabilities will be used to generate requirements to the Level 2 discipline teams. Similarly, the uncertainty in the Level 3 tools, as well as the resulting increase in design margin to accommodate this uncertainty, will be communicated to Level-4 to perform the technology assessment activities. The details within the Propulsion System Design, Vehicle System Design, and Experimental Capabilities elements are discussed below, following a brief discussion of the general approach to achieve the level 3 objectives.

Given that the emphasis is on fundamental technology development and not the design and development of a specific vehicle design, the Level 3 resources are very limited; thereby, leading to an innovative approach to meet Level 3 objectives. The approach is to utilize a Vehicle Technology Integrator and a Propulsion Technology Integrator to leverage and integrate the technology development activities with the other discipline teams (heavily focused on Level 2 and 4) and other Aero Projects to focus a portion of their work towards multi-disciplinary tool development. They will then work with OGA s and/or other NASA Mission Directorates to secure partnerships that will provide experimental validation data for these tools and methods. This tool and method development approach is considered feasible, since the Aero Projects plan to use Interdisciplinary Groups (IDGs) to work across projects to leverage efforts and resources on interdisciplinary work. The validation approach is also believed to be feasible because there are significant incentives for OGA s and other NASA Mission Directorates to work with the Hypersonics Project on validation experiments.

The NASA Hypersonics Project has unique flight and ground test experience, as well as proven design and analysis capabilities. These capabilities have already been leveraged to form productive partnerships with DoD on Programs such as X-51 and FRESH-Fx. Hypersonics Project members also hold key technical advisory or implementation roles in other DoD Programs such as DARPA Falcon, and NASA Programs such as CEV. The Project plans to use these Project members to facilitate other partnerships of benefit to both parties. While these DoD and NASA Programs may not align exactly with the focus that the project has chosen with the HRRLS and HMMES missions, the basic physical phenomena, and the interactions between them that are to be verified, are often common. Thus while an engine test of the flight weight, closed-loop fuel cooled, X-51 scramjet engine, fully integrated to an airframe cannot validate all aspects of an interdisciplinary propulsion systems design methodology being developed for HRRLS mission, it can provide validation for significant portions of the methods. Better yet, the difference between a cruise optimized TBCC system developed for a DoD Program like Falcon, and that developed for a HRRLS mission are minor in most respects, and data from such a system would provide nearly all validation required for HRRLS propulsion system design methodology.

HYP.3.01—Propulsion Systems Design

While the Hypersonics Project will develop predictive tools and methodologies to design and analyze the complex combined cycle engines required for hypersonic airbreathing propulsion systems, as stated above, the Project will not be able to conduct verification test programs for these systems. In order to obtain this critical verification data, the Project will aggressively seek collaborative activities with DoD, and potentially industry in this area.

The key propulsion system issues relate to integration of high and low-speed propulsion systems into a combined cycle system. Controlling this combined propulsion system at all power settings and flight points such that adequate and predictable propulsive forces and moments are achieved, while maintaining structural loads (pressure, thermal, and unsteady) at acceptable levels to provide required system life is the major challenge. One key area that needs to be further investigated is the mode-transition from low-speed to high-speed propulsion. While both TBCC and RBCC systems will be investigated under the Hypersonics Project, TBCC system level design work is the near term emphasis for the HRRLS mission as stated in the Relevance section. Therefore the major level 3 Propulsion milestones are focused on TBCC design methodology development.

The key to designing and predicting the performance and operational aspects of these combined cycle systems is to bring higher level tools to bear on the problem. Emphasis will be placed on bringing technical advancements in boundary layer transition, turbulence, combustion, heat transfer and time dependent modeling to level 3 combined cycle engine challenges and coupling these predictive fluid dynamics elements with advanced structures and controls tools.

Prior to full combined cycle work, slightly simpler test cases for predictive methods will be made available through existing collaborative test programs being conducted by NASA and USAF on two flight-weight closed-loop fuel-cooled scramjet engines, in FY06 and FY07. Testing of the Ground Demonstration Engine-2 (GDE-2) at Mach 5 flight conditions to demonstrate/verify closed-loop operations of a flight-weight, hydrocarbon-fueled, fuel-cooled structure, dual-mode scramjet has just been completed in the 8-Ft HTT. Milestone HYP.3.01.36 will be achieved through a collaborative test of the USAF Scramjet Engine Demonstrator (SED) X-51 Program SJX61-1 ground test engine. The test is designed to provide the Air Force with engine performance and operability verification data prior to flight of the X-51, and provides NASA an early look at modeling and method gaps, and a validation data set for many aspects of a TBCC design methodology. This test will also occur in the 8-Ft HTT.

Milestone HYP.3.01.29 will be partially achieved through an in-house design effort on a HRRLS mission compatible TBCC engine system. Mechanical and systems design and performance predictions for the propulsion system, including the integrated turbine engine and ram/scramjet flowpaths will be completed. Critical details such as thermal protection (cooling, oxidation, etc.), power balancing, and predictions of weight and safety factors will be included. The design level will be compatible with a 5% error in performance and 10% on system weight, but verification of these values will only occur if a partnership can be established to build and test the system. Even if such a partnership is not achieved, the design exercise forces high level integrated design tools to be engaged, allowing gaps to be identified that can lead to further methods improvements. The likely collaboration partners for TBCC work are DARPA on the Falcon HCV Combined Cycle Engine Program.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
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Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.3.01.36 2007 Q4	AF/NASA Collaborative T&E of X-51 Engine	HYP.3.01.35 X-51 Partnership in place	Testing of the AF SED Program SJX61-1 ground test engine in 8-Ft HTT provides engine development and verification prior to flight. This collaborative effort leverages NASA's ground test capability for a major DoD flight test program, X- 51, and provides validation data set for NASA developed tools.	NASA Metrics are to have agreement between pre-test predictions and test data for engine performance within 5% and operating limits within 0.1 phi, and coolant system performance within 10% bulk exit temperature for a given throttle setting.	Preliminary data reports and analysis of engine performance, cooling system operation, engine control system operation
HYP.3.01.29 2011 Q4	Propulsion System Design for TBCC TSTO HRRLS mission	HYP.4.01.06, HYP.3.01.29a-30 HYP.3.01.36 HYP.2.02.P3 HYP.2.01.33 numerous other L1&2 MS Requires DoD or Industry Partnership for validation	Mechanical and systems design and performance predictions of a TBCC propulsion system including the integrated turbine engine and ram/scramjet flowpaths. Includes thermal protection (cooling, oxidation, etc.), power balancing, and predictions of weight and safety factors. Enables higher level design tools to be engaged, gaps analyzed.	2010 Preliminary design. 2011 Final Design to meet HRRLS mission requirements. Uncertainty on performance specified at 5%, weight 10%, Validation requires partnership for fabrication and test of design, Most likely candidate, DARPA Falcon HCV Combined Cycle Engine.	TBCC Engine system final design. Design tool gap analysis report.

HYP.3.02—Vehicle Systems Design

As is the case with Propulsion Systems at level 3, the Hypersonics Project will work to develop tools and methodologies to design and analyze the highly coupled multidisciplinary systems problems presented at level 3, but the Project will not have resources to conduct methods and tools validation experiments. Therefore it is important to develop collaborations with DoD or other NASA Programs where appropriate multidisciplinary system level test programs will be conducted. Several examples of key areas where we will seek collaboration are described in this section.

Detailed aero assessment will be made of a reference vehicle using the most up-to-date aero, aerothermodynamic, aerothermoelastic prediction methodologies available. Preferably, this assessment will be made on a relevant flight vehicle from a DoD program, most likely the X-51 or Affordable Responsive Spacelift-Subscale Demonstrator (ARES-SD). Alternatively if flight test schedules do not permit this assessment at an appropriate time in the development schedule of the tools and methodologies, a HRRLS mission compatible vehicle concept will be utilized. The goal of this assessment will be to understand the gaps in modeling within tools, and gaps between discipline tools that must still be bridged. One result of this assessment will be achievement or partial achievement of milestone HYP.3.02.64, which aims to validate coupling of aero/aerothermal/acoustics prediction methods with thermal and structural response prediction methods. If appropriate instrumentation can be made available during appropriate ground and/or flight tests of ARES-SD, Falcon HTV or X-51 these methods could be validated.

These methods will also be critical to a class of HMMES related technologies; inflatable hypersonic decelerators. For flexible inflatable decelerator systems additional complexities are present. Nonlinear equations within the structures solver, such as finite element models (FEM), with proper coupling with CFD codes are required to model the intense fluid-structure interactions (FSI) that occur during hypersonic entry into a planet's atmosphere. The mechanism for coupling the structural codes with the appropriate CFD codes for calculating aerothermal flow characteristics within the hypersonic flow field during convergence of the FEM matrices are undeveloped. NASA ESMD and SMD supported

researchers have begun an initial benchmark program for developing these tools, through the SBIR and In-Space Propulsion (ISP) programs. The limited resources recently provided by the SBIR and ISP program are targeted for initial exploration and development of the coupling between the structural and fluid codes. The Hypersonics Project plans to explore collaboration with SMD and ESMD to build upon this initial effort, and provide the next generation of tools to design and analyze inflatable decelerator systems at hypersonic speeds. Verification opportunities will be sought.

A key goal for future hypersonic vehicle airframe concepts is to evolve from externally-insulated TPS to integrated structural TPS and hot, load-bearing structures. For these structures, the aerothermal environment (amount of heating to the vehicle surface) depends significantly on the distribution of the temperature on the surface. In the current vehicle design process, this tight coupling between the flow field and the structure is either neglected completely or taken into account through numerous global iterations between aerothermodynamics CFD and structural heat transfer analysis. Alternatives to this inefficient and inaccurate approach are required to provide a means to optimize structural designs for minimum weight. To achieve milestone HYP.3.02.41, initial methodologies for integrating aerothermodynamics CFD methods with the thermal-structural methods from the level 2 Discipline Teams will be developed for this tightly coupled problem. It is anticipated that these methods will be verified with combined loading tests and flight data obtained in the ARES-SD, Falcon HTV, and/or the X-51 Program.

The coupling between the flow field and vehicle surface is more complex for re-entry vehicles with ablative TPS where the shape of the surface changes as ablation occurs and byproducts are released from the surface into the flow. Methodologies for coupling these fluid-structure interactions will be extended to ablative TPS. Opportunities will be sought to verify these methods against ground or flight data.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.3.02.41 2010 Q4	Integrated Airframe Structure methods	HYP.2.03.03 HYP.2.01.01 HYP.2.01.25 Requires DoD or Industry Partnership for validation	Tests of integrated structural systems must be performed to demonstrate interactions between components during exposure to flight-like loads and temperatures and to identify design tool gaps.	Predictions within 10% of measured quantities. Validation requires partnership for fabrication and test of test article. Most likely candidate ARES-SD.	System design documentation, test data and design tool gap analysis report.
HYP.3.02.64 2011 Q4	Integrated Analysis Tools for Airframe Structures	HYP.3.02.41 HYP.2.03.02-03 HYP.2.01.47 HYP.2.01.02 Numerous other L1 & 2 in all disciplines. Requires DoD partnership for validation	Coupling and validation through tests of aero/aerothermal/acoustics prediction methods with thermal and structural response prediction methods. Initial efforts to focus on aerothermoelasticity.	Predictions within 10% of relevant flight or ground data. Validation requires partnership, most likely X-51 and/or ARES-SD.	Documentation of analysis tools and test results. Report on tool gaps remaining.

HYP.3.03—Experimental Capabilities

The Hypersonics Project will not make significant financial contributions to upgrading ground test facilities for complex level 3 testing. The project will work closely with the NASA Aeronautics Test Program and DoD to assess the national need for, and assist in defining any upgrades to facilities that are undertaken for their programs. Measurement techniques developed by NASA are expected to augment any NASA and DoD test programs at this level.

NASA will also work with DoD to develop low-cost flight test and in-flight measurement capabilities to obtain hypersonics data at all levels. For example the Hypersonics Project is already collaborating with the USAF on the use of sounding rockets to obtain level 1 and 2 data under the FRESH-Fx Program.

The Project is also currently doing a feasibility study on using surplus Phoenix missiles as a flight testbed for level 1 and 2 experiments that require a flight control system. If this testbed appears feasible, cost effective to operate, and useful experiments are defined, the plan is to try to engage the USAF and U.S. Navy (USN) in developing the system for experimental use. Finally, initial discussions have occurred between the project and the USAF on use of the X-51 and/or the ARES-SD as a testbed vehicle for other hypersonics experiments following the baseline flight test program. The project plans to work with the USAF and their contractor teams to define potential follow-on experiments for both systems.

HYP.4.01—PB-MDAO Technical Approach

The primary objective of the Hypersonics Project is to expand our scientific and engineering knowledge base of all hypersonic-related aeronautics challenges. One of the principal goals of this endeavor will be the development of physics-based multi-disciplinary predictive design, analysis and optimization tools incorporating uncertainties. While broad enough to analyze any of the missions shown in Figure 1, these tools will be focused on supporting the two primary missions established by the Project, HRRLS and HMMES. The principal challenges in achieving this goal for the Systems Analysis Discipline Team (SADT) are the introduction of high fidelity physics into the analysis process and design environment, quantification of uncertainty in design through probabilistic methods, reduction in design cycle time, and the development and implementation of robust processes and tools enabling a wide design space and associated technology assessment capability. The SADT is responsible for providing the Project with the decision-making information it needs to properly guide technology and analytical tool development. Credible, rapid, and robust system analysis processes and design tools are required by the SADT in order to generate this information. All of the major way points and milestones that the SADT has developed, table shown below, support these challenges and are described in more detail below.

Baseline L4 SOA Design Tools (HYP.4.01.14).—One of the first tasks the SADT will undertake will be to review the suite of tools currently used to perform conceptual hypersonic vehicle design and analyses, to standardize a set of definitions that describe their levels of fidelity, to assess their predictive uncertainty, and to identify any capability gaps or inadequacies that may be present. The tool suite employed by the SADT must encompass the broad range of the more traditional technical disciplines associated with the two primary mission classes (HRRLS and HMMES) being addressed by the Project, as well as the life cycle suite of predictive tools (system reliability, life cycle cost, etc.). While selecting these two mission classes, the Project has also established the primary FOM for each mission, high mass delivered to the surface for the HMMES and high system reliability for the HRRLS. The SADT has already identified its life cycle tool suite as a high priority area for upgrading and plans to do so through several avenues including by way of contracting with industry, through in-house development, and through an NRA.

Annual Technology Portfolio Assessment (HYP.4.01.05).—Progress in technology development will be tracked by assessing their impact toward meeting the stated goals and FOMs of the Project's two primary missions. This research and technology (R&T) assessment process will evaluate the system-level impacts of given research pursuits and technology development efforts and provides guidance to formulate R&T investment strategies. It identifies investment opportunities to maximize performance and robustness while minimizing cost and risk. Tasks include the development of an R&T database, performing system level sensitivity analysis, quantifying the impact of these R&T pursuits against key capability metrics (mission performance, FOMs, utility, etc.), and producing a prioritized portfolio. Finally, the impact of budget, schedule, risk and policy constraints on the portfolio through sensitivity analysis is evaluated. Benefits of the assessment process include the ability to perform regular, structured, and quantitative evaluation of R&T activities, as well as improved long-term strategic planning.

Tool and Method Review (HYP.4.01.19).—In coordination with the Hypersonics Project level 1, 2 and 3 teams, the SADT will establish an annual, project-wide review of analytical tools in order to track their development, validation, and uncertainty reduction progress. During this review, new shortfalls in analytical capability may be identified while existing deficiencies may have been eliminated throughout the previous FY by bringing new capabilities on-line. In addition, uncertainty levels for each of the level 4 tools will eventually be quantitatively assessed through validation. The SADT also expects to work with its partners at the AFRL on its ARES-SD, which should provide, among other things, a wealth of data on performance and design characteristics as well as supportability and maintainability information for a highly operable launch vehicle. In partnership with AFRL the SADT proposes to provide systems analysis support to both the ARES-SD and the Air Force's X-51 projects. This would provide the SADT with two excellent flight demonstration systems for bench-marking their level 4 suite of tools.

PB-MDAO Integrated Capability (HYP.4.01.12) and Improved Tools and Methods

(HYP.4.01.10).—Being able to accurately model, analyze and optimize the high level of discipline coupling and integration that is characteristic of hypersonic systems is the key to unlocking their performance potential. Top level requirements for the design environment include support of a collaborative inter-disciplinary tool suite including parametric geometry generation, streamlined data transfer between analysis tools, automated coupling and execution of computational analyses, multi-disciplinary design optimization methods, and probabilistic methods and processes that enable system level risk assessment /mitigation and robust vehicle configuration optimization. The goal is to bring this environment on-line in the third year of the project, and then work to improve its efficiency, accuracy, and robustness. The SADT will leverage existing collaborative efforts in the development of an integrated design, analysis and optimization environment that will incorporate increasingly higher fidelity tools, including those tools developed by the level 1, 2 and 3 discipline teams. The SADT will also review research within the SBIR Program targeting MDO methods and uncertainty and consider it for inclusion within this tools and methods development approach. In addition, the SADT will participate in and work with the Systems Analysis Working Group (a proposed subsonic/supersonic/hypersonic cross-project team) to explore potential areas of collaboration, including the development of individual discipline tools and integrated design environments, as well as sharing and developing relevant databases.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.4.01.14 2007 Q2	Baseline L4 SOA design tools		Establish a baseline suite of discipline level analytical tools with fidelity levels consistent with "standardized" definition. Establish qualitative uncertainty levels for all level 4 specific tools (quantitative levels to be established as part of tool development and tool review process).	Waypoint – no metric available	Documented SOA baseline for L4 milestones. A baseline level of uncertainty on level 4 FOMs will be established, as will a measure for design cycle time and baseline level of analytical fidelity for each discipline.
HYP.4.01.05 2007-2015 Q2	Annual technology portfolio assessment	All funded level 1, level 2, and level 3 efforts	As part of the annual cycle of systems analysis, the SADT will gather technology information and evaluate selected technologies on the current project reference missions. At the end of the assessment, SADT will conduct a project wide review of results.	Waypoint – no metric available	Report on tech assessment. Effect of technologies on mission level FOMs. Used by Project management to establish priorities and refocus the Project as new knowledge is gained.

Number/ Year	Milestone Title	Dependencies	Description	Metrics	Deliverable
HYP.4.01.19 2007-2015 Q4	Tool and method review		As part of the annual cycle of systems analysis, the SADT will continuously incorporate tools from L1-3 and develop and improve L4 tools and integrated environment. Annually, there will be a project wide review of the tools and methods to be used at level 4. Gaps in capability, tool and method uncertainty, and their development status are reviewed. In addition, documentation of applicability and proper use of tools within stated uncertainties are reviewed.	Waypoint—no metric available	Report on tools assessment. <ul style="list-style-type: none"> • identified new gaps in tool capability • closed existing gaps in tool capability • quantitatively assessed tool predictive uncertainty Used by Project management to establish priorities and refocus the Project as new knowledge is gained.
HYP.4.01.12 2009 Q4	PB-MDAO integrated capability	HYP.3.01.27 HYP.4.01.10 HYP.4.01.13 HYP.3.02.31 HYP.3.02.34 HYP.3.02.42	The predictive design tools are developed and integrated into a new design environment allowing simultaneous optimization of performance, safety /reliability, and life cycle cost. This geometry centric environment will allow full, system-wide MDO capability, while supporting automated grid generation and rapid system uncertainty analysis.	<ul style="list-style-type: none"> • Grid generation and paneling 10X faster than current capability • Number of variables and constraints handled by MDO increased by 5X 	Documentation of new architecture and capabilities.
HYP.4.01.10 2011 Q1	Improved methods/tools	HYP.4.01.01 HYP.3.01.25 HYP.3.01.22 HYP.3.02.44 HYP.4.01.03 HYP.3.03.08	The steps to achieve the desired predictive simulation capabilities for design are to reduce predictive uncertainty on level 4 FOMS, to reduce the design cycle time, and increase the overall fidelity of the baseline suite of level 4 analysis tools.	<ul style="list-style-type: none"> • Level of uncertainty of level 4 FOMS is reduced by 25% • Design cycle time at a given level of fidelity is reduced by a factor of 2 • Overall fidelity of the suite of L4 tools is increased by one level of fidelity (relative to initial baseline HYP.4.01.14) 	Significantly improved PB-MDAO design system and individual discipline methodologies for hypersonic missions, documented and available for NASA, DoD and industry use.

Appendix A—Acronym List

8-Ft HTT	8-Ft High-Temperature Tunnel	FTE	full-time equivalent
AFRL	Air Force Research Laboratory	GDE-2	Ground Demonstration Engine-2
AHSTF	Arc-Heated Scramjet Test Facility	GN&C	guidance, navigation & control
ALV-X1	ATK Launch Vehicle Experiment 1	GPC	general predictive control
ARC	NASA Ames Research Center	GRC	Glenn Research Center
ARES-SD	Affordable REsponsive Spacelift-Subscale Demonstrator	GVT	Ground Vibration Testing
ARMD	Aeronautics Research Mission Directorate	HF	Hypersonic Fellows
C/C	carbon fiber, carbon matrix composite	HFE	Hypersonic Flight Experiments
C/SiC	carbon fiber, silicon-carbide matrix composite	HFR	Hypersonic Fundamental Research
CARS	coherent anti-Stokes Raman spectroscopy	HiSPA	High Speed Propulsion Assessment
CEV	Crew Exploration Vehicle	HMMES	High Mass Mars Entry Systems
CFD	computational fluid dynamics	HRRLS	Highly Reliable Reusable Launch Systems
CHSTF	Combustion-Heated Scramjet Test Facility	HTV	Hypersonic Technology Vehicle
CMC	ceramic matrix composite	HTF	Hypersonic Tunnel Facility
CMD	computational materials design	HTHL	horizontal take-off horizontal landing
Co-I	Co-Investigator	HyBoLT	Hypersonic Boundary Layer Transition
CPM	Center Project Manager	HyPULSE	Hypersonic Pulse Facility
CS	civil servant	IDG	Inter-Disciplinary Groups
DARPA	Defense Advanced Research Projects Agency	ISP	In-Space Propulsion
DCR	Durable Combustor Rig	JANNAF	Joint Army/Navy/NASA/Air Force
DDR&E	Director of Defense Research and Engineering	LaRC	NASA Langley Research Center
DoD	Department of Defense	LES	Large-Eddy Simulation
DFRC	NASA Dryden Flight Research Center	M&S	Materials and Structures
DGV	Doppler Global Velocimetry	NASA	National Aeronautics and Space Administration
DNS	direct numerical simulations	NASP	National Aero-Space Plane
DTRMC	Defense Test Resource Management Center's	NCC	National Combustor Code
ECRL	Engine Components Research Laboratory	NGLT	Next Generation Launch Vehicle Technology
EDL	entry, descent, and landing	NDE	non-destructive evaluation
ERB	Engine Research Building	NIHR	NASA Institute for Hypersonic Research
ESMD	Exploration Systems Mission Directorate	NIM	NRA Implementation Manager
FaCET	Falcon Combined Cycle Engine Technology	NO	nitric oxide
HYPERSONICS	Fundamental Aeronautics Hypersonics	NRA	NASA Research Announcement
FAP	Fundamental Aeronautics Program	NRC	National Research Council
FEM	finite element models	OML	outer mold line
FOMs	figures of merit	ONR	Office of Naval Research
FR	Flight Research	OSD	Office of the Secretary of Defense
FRESH-Fx	Fundamental RESearch from Hypersonic Flight Experimentation	PAI	Propulsion-Airframe Integration
FSI	fluid-structure interactions	PB-MDAO	physics-based multi-disciplinary analysis and optimization
		PI	Principal Investigator
		PIV	particle image velocimetry
		PLIF	Planar laser-induced fluorescence
		PM	Project Manager
		PMC	Program Management Council
		POC	point of contact
		PS	Project Scientist
		R&D	research and technology development

R&T	research and technology
RANS	Reynolds-averaged Navier-Stokes
RBCC	rocket-based combined cycle
RCS	Reaction Control System
RFI	Request for Information
SAA	Space Act Agreements
SADT	Systems Analysis Discipline Team
SBIR	Small Business Innovative Research
SED	Scramjet Engine Demonstrator
SiC/SiC	silicon-carbide fiber, silicon-carbide matrix composite
SMD	Science Mission Directorate
SOA	state-of-the-art
SOAREX	Sub-Orbital Aerodynamic Re-entry Experiments
SSTO	single-stage-to-orbit

S&T	Science and Technology
SWT	Supersonic Wind Tunnel
T&E	test and evaluation
TBCC	turbine-based combination cycle
TDALS	tunable diode laser absorption spectroscopy
TIM	Technical Interchange Meetings
TPS	thermal protection systems
TSP	temperature sensitive paint
TSTO	two-stage-to-orbit
USAF	U.S. Air Force
USN	U.S. Navy
VSE	Vision for Space Exploration
VTHL	vertical take-off horizontal landing
WYE	work year equivalent